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Spatial and Temporal Evaluation of the Frequency of Thunderstorms and their Effects on PM2.5 Distribution over Baghdad and Basra Airdromes

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Abstract: Particulate matter 2.5 is one of the primary components of air pollution. Sources of PM2.5 may be natural or anthropogenic. The main sources of the pollutants in Iraq include burning natural gas, oil, and power plants. The study is based on archived datasets from the Iraqi Meteorological Organization and Seismology and satellite data available from ECMWF and NASA for a ten-year period in Baghdad and Basra Airdromes. The spatial and temporal analysis showed that the highest frequency of thunderstorms occurs in April about 64.03%. The highest annual frequency of thunderstorms was for Baghdad Airport station in 2018 and 2002 (20 days) and Basra Airport station in 2003 and 2018 (13 days). The PM2.5 concentration at Baghdad Airport and Basra Airport stations prior to, during, and following the storm was of the category D of the air quality indices. The concentration kept growing without addressing the causes. It looks like the rise in PM2.5 concentrations that thunderstorms increased in the station is caused by arid thunderstorms and the storm's downdrafts, which lift dust upwards. This leads to PM2.5 concentrations remaining in the atmosphere for a longer period. As the Normalized Difference Dust Index results indicate, 90–95% of Baghdad is situated in areas with moderate dust levels for the period 2000-2019, while 95% or more of Basra is situated in areas with moderate to high dust levels for the same period.

Keywords: Particulate matter PM2.5; Dust storms; Air quality; K-index; NDDI.

1. Introduction

A thunderstorm is a convective storm producing lightning and thunder, usually developed within cumulonimbus clouds. When warm, humid surface air is covered by cold, dry air in the atmosphere the atmosphere becomes conditionally unstable, a thunderstorm is likely to form. The life cycle of a thunderstorm progresses through three stages.

In the developing stage, cumulus clouds grow as rising air currents (updrafts) dominate, with occasional lightning but little or no rain. The storm then enters its mature stage, characterized by simultaneous updrafts and downdrafts as precipitation falls, producing gust fronts and often severe weather such as strong winds, hail, frequent lightning, heavy rain, and sometimes tornadoes. Finally, in the dissipating stage, downdrafts suppress the updrafts, leading to a rapid decline in storm intensity and widespread precipitation [1]. Thunderstorm activity is a recognized meteorological mechanism for generating localized dust storms, or haboobs. This phenomenon is a consequence of strong downdrafts and convective outflows that can mobilize surface sediments, a process particularly common in arid environments. Haboobs, are thunderstorms that produce localized dust storms, are known to occur in Iraq and significantly affect the region's air quality [2,3]. According to a study, a rise in pollution levels significantly increases the frequency of lightning strikes during atmospheric instability, particularly when those strikes occur from clouds to the ground. This is because pollution enhances the processes within clouds, increasing their strength and activity [4]. Due to climate change and global warming, which have increased the frequency of dust storms in recent years, there are also experiences of numerous dust storms in Iraq, which lead to desertification and absence of green cover [5]. PM2.5 is the airborne particles that are 2.5 micrometers in diameter or less, comprising a complex combination of substances and containing organic matter, nitrates, elemental carbon, sulfates, ammonium, and dust particles. They are able to stay long periods in the atmosphere due to their small size and light weight, making them easily affected by varying weather conditions. These particles are important environmental pollutants that require monitoring and control due to their serious health effects on humans. They are capable of penetrating deeply into the respiratory system and lungs and can carry bacteria, microorganisms, and viruses. They are natural and humans in the origin of these particles, e.g., combustion of fossil fuels and industrial processes [6, 7]. The sources of atmospheric pollution are mainly due to the combustion of fossil fuels, industrial processes, power generation, generators and heating. Moreover, the main causes of the emissions of pollutants are the brick, cement, and asphalt sectors, transportation, agriculture, fires, and dust storms. In addition to dust, another anthropogenic source that has highly diversified the quality of air in Iraq is the emission of power plants, the use of household and public generators in massive numbers due to power outages, the increasing transportation activity, fossil fuel combustion for heating, and uncontrolled waste burning, all of which release large amounts of pollutants into the atmosphere [4]. In order to identify and track these storms, remote sensing is crucial. Despite the fact that dust storms can be identified using a variety of methods, it is difficult to recognize and find these storms in semi-arid areas [8]. Normalized Difference Dust Index (NDDI) can be utilized in this study to identify storms and separate them from clouds and yellow lands. Another technique for identifying dust storms is the Brightness Temperature Variation (BTV) [9]. On April 15, 2021, the Beijing region had an unusual dust-thunderstorm that included frequent lightning, dirt precipitation, and gusts. The findings demonstrated that dust particles from Mongolia were engaged in the thunderstorm's growth process based on extensive data from satellite, in-situ observation, weather radar, and reanalysis data. PM2.5 and PM10 levels rose quickly, peaking at 1500 $\mu g/m^3$ and 250 $\mu g/m^3$, respectively. A large percentage of +CG lightning was expected to originate from the dust aerosols functioning as effective ice nuclei (IN) and cloud condensation nuclei (CCN) penetrating the thunderstorm and increasing the concentration of ice-phase particles and supercooled water [10]. The remote sensing techniques have been used in identifying dust storms in semi-arid regions. These metrics include the Norma Diffusion Dust Index (NDDI) and Brightness Temperature Variation (BTV), which might be able to discriminate between dust storm pixels and other features in satellite images in order to identify these events in areas that otherwise would be hard to differentiate between desert areas and other features [11]. To evaluate the aerosol and thermodynamic settings around thunderstorm commencement, a multi-variable study of thunderstorm environments in two different geographical regions is carried out.

Thunderstorms that occurred within a 225 km radius are reconstructed using 12 years of cloud-to-ground (CG) lightning flash data. There were 310,209 thunderstorms in Kansas City and 196,836 in Washington, D.C. There is evidence that the thermodynamics, aerosol characteristics, and aerosol concentrations of warm-season thunderstorm settings under benign synoptic conditions differ significantly between the two regions. Despite the variations in their ambient surroundings, thunderstorm intensity seems to be controlled by similar thermodynamic-aerosol connections. Convective available potential energy (CAPE) and flash counts have statistically significant positive correlations when analyzing thunderstorm initiation conditions. Additionally, aerosol concentration seems to be a more significant factor for lightning enhancement than particle size [12]. The researcher studied the impact of PM2.5 particles associated with thunderstorms over Iraq between 2000 and 2009 using archived datasets from the Iraqi Meteorological Organization and Seismology and Landsat 8 data to calculate PM2.5 and NDDI. The findings were as follows: The PM2.5 concentration before, during, and after the storm was (B) (12.1-35.4 μg/m³) at Khanaqin station and (D) (55.5-150.4 μg/m³) at Basra Airport station, which is the prevailing frequency. Non-rain thunderstorms with low relative humidity are the reason behind the rise in PM2.5 concentrations in the D, E, and F categories (55.5-150.4, 150.5-250.4, and 250.5-500.4 μg/m³) in thunderstorms for stations. As a result of the soil drying out and breaking up, in addition to the downdraft and updraft winds caused by the storm, over time the concentrations of PM2.5 (dust) in the atmosphere rise. Indicate to the NDDI's results, 90–95% of Baghdad is at risk for air pollution that has an impact on people's health and welfare. Between 2000 and 2009, the dust levels were low to moderate, and from 2013 to 2023, they were moderate to higher [13]. The study of thunderstorms and their impact on PM2.5 particles aims to understand how extreme weather events (thunderstorms) affect the properties (concentration) of fine particulate matter, impacting air quality and consequently the climate, health, and environment due to their warming or cooling effects. It also explores how thunderstorms, particularly those accompanied by dust storms, contribute to increased concentrations of fine particulate matter in the atmosphere by stirring up dust and sand from the ground, especially in arid regions (dry climates), based on meteorological and remote sensing data. The basic idea is to link dynamic weather factors (thunderstorms) and pollution levels (PM2.5) to better predict air conditions and ensure the health and safety of the population and the environment. This study will later be used with models for predicting severe weather phenomena, so that its results will help in developing and improving climate models and air quality prediction models, to be more accurate during and after thunderstorms.

2. Materials and Methods

Iraq is located in northeast of the Arabian Peninsula, between 29˚5′–37˚22′N and 38˚45′–48˚45′E. The country's four main regions—the steppe terrain area has a semi-arid climate, the mountain range has a Mediterranean climate, whereas the alluvial plain and desert plateau have a hot desert temperature—all possess various climates [14]. Figure 1 shows the topography of Iraq and the locations of the selected stations Baghdad and Basra Airport—with detailed descriptions provided in the Table 1.

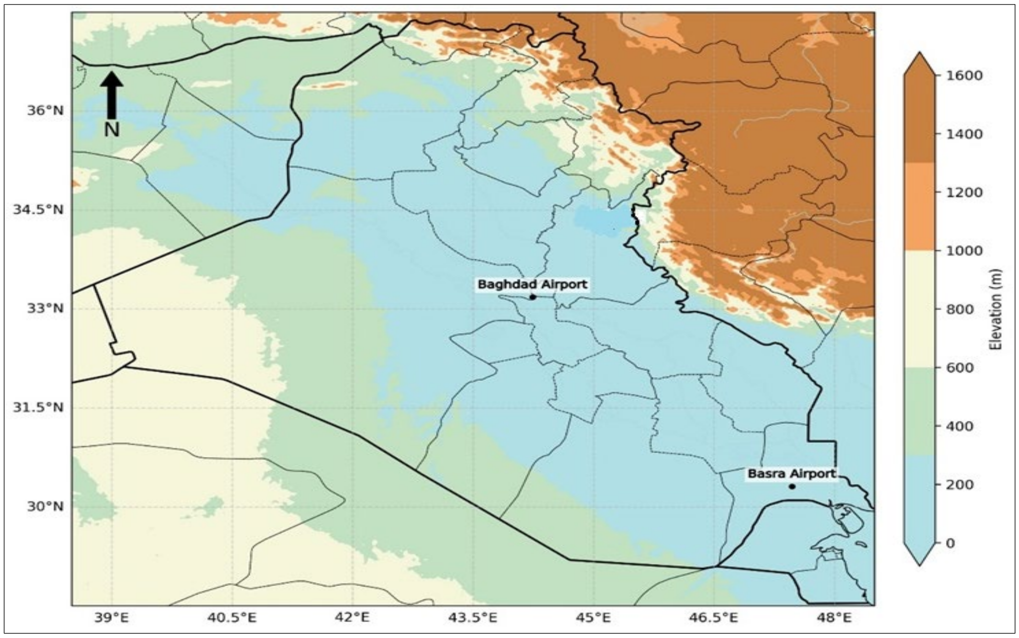

Figure 1. Map of Iraq with the selected stations.

Table 1. Weather Stations Information.

Station	**Station no.**	**Longitude**	**Latitude**	**Height (m)**
Baghdad Airport	650	44.24° N	33.18° E	31.7
Basra Airport	690	47.47° N	30.31° E	2.6

2.1. Data sources

2.1.1. Meteorological Stations Observations

Hourly meteorology data were obtained in real time from the Iraqi Meteorological Organization and Seismology, the data were collected from weather stations distributed across Iraq, with their quality and continuity assessed before analysis.

2.1.2. ERA-Interim Reanalysis Data

The ERA5 data for the period (2000-2019) was used at 00, 06, 12, and 18 UTC with a spatial resolution of 0.25° × 0.25° for the pressure levels 850, 700, and 500 hPa [15].

2.1.3. Reanalysis Data (MERRA-2)

The MERRA-2 data was used in this investigation: bias-corrected global hourly surface PM2.5 mass concentration data from 2000 to 2019 at 00, 06, 12, and 18 UTC with a spatial resolution of 0.5° x 0.625°, and the dataset has integrated 72 vertical layers, and they cover more than 80 km [16-18]. The accompanying Table 2 provides specifics on the classification criteria for PM2.5 concentrations.

Table 2. Classification of PM2.5 concentrations [13].

PM2.5	**concentration ($\mu g/m^3$)**
A	(0-12)
B	(12.1-35.4)
C	(35.5-55.4)
D	(55.5-150.4)
E	(150.5-250.4)
F	(250.5-500.4)

2.1.4. Landsat-5 and Landsat-8 Datas

The study examined dust activities in Baghdad and Basra, as Iraq is an area known for its arid climate, using Landsat-5 Thematic Mapper (TM) and Landsat-8 Operational Land Imager (OLI) imageries. Each pixel in the generated image was categorized according to its NDDI range in order to measure and illustrate the spatial distribution of dust [20]. A summary of the data is shown in Table 3.

Table 3. Landsat-5 TM and Landsat-8 OLI models overview.

Properties (model)	Landsat-5 TM	Landsat-8 OLI
Spatial resolution	30 m (Bands 1-5 and band 7), 120 m (Band 6)	15 m (Band 8), 30 m (Bands 1-7 and band 9), 100 m (Bands 10 and 11)
Bands of spectrum	7 bands, covering coastal, NIR, SWIR, and thermal	11 bands, covering coastal, NIR, SWIR, and thermal
Size of the scene	170×185 km	185 ×180 km

2.2. Calculations of Some Indices

2.2.1. K-index

The K-index is a thunderstorm potential indicator that is based on the amount and vertical extension of low-level moisture in the atmosphere as well as the vertical temperature lapse rate. Temperature (T) and relative humidity (RH) were used to calculate the dew point (Td) and the dew point depression(DD=T-Td) which then were used to calculate the K-index as in the following equations [20, 21].

$$Td = (243.04 * [\ln(RH / 100) + ((17.625 * T) / (243.04 + T))]) / (17.625 - [\ln(RH / 100) + ((17.625 * T) / (243.04 + T))]) \quad (1)$$

$$K = T\ (850\ mb) + Td\ (850\ mb) - T\ (500mb) - DD\ (700\ mb) \quad (2)$$

A potential thunderstorm can be determined by the value of the K-index as shown in Table 4.

Table 4. Atmospheric stability is based on the K-index value [21].

Number	K-Index Value (°C)	Thunderstorm Probability (Types)
1	K below 20	None
2	K between 20 to 25	Isolated thunderstorms
3	K between 26 to 30	Widely scattered thunderstorms
4	K over 31 to 35	Scattered thunderstorms
5	K = 40 or Above 35	Numerous thunderstorms

2.2.2. NDDI Calculation

Dust concentration was detected and evaluated using the Normalized Difference Dust Index (NDDI). Eq. 3 uses the surface reflectance data from the SWIR2 and blue bands to determine the NDDI.

$$NDDI = \frac{(R_{SWIR2} - R_{Blue})}{(R_{SWIR2} + R_{Blue})} \quad (3)$$

where: Landsat-5: R_{SWIR2} is the surface reflectance from Band 7 (SWIR2: 2.08 – 2.35 µm), R_{Blue} is from Band 1 (Blue: 0.45 – 0.52 µm); and Landsat-8: R_{SWIR2} is the surface reflectance from Band 7 (SWIR2: 2.11 – 2.29 µm), R_{Blue} is from Band 2 (Blue: 0.45 – 0.51 µm). After filtering all Landsat-5 and Landsat-8 scenes by cloud cover (less than 20%), pixel-level quality assurance (QA_PIXEL) masks were used to further eliminate cloud and shadow contamination.

Scale factors from USGS documentation were used to translate surface reflectance measurements. NDDI was calculated for every scene after masking each image. A mean yearly NDDI map for 2000–2019 was then created by combining all valid NDDI values, to offer a dust severity analysis that is easier to understand [22]. As shown in Table 5, the NDDI results were divided into six distinct dust intensity groups.

Table 5. NDDI-based classification of dust severity in the study area [22].

Class	NDDI Range	Description
1	≤ 0.00	No dust / Vegetation
2	0.00 – 0.10	Very low dust
3	0.10 – 0.20	Low dust
4	0.20 – 0.30	Moderate dust
5	0.30 – 0.40	High dust
6	> 0.40	Severe dust / Dust storm

3. Results and Discussion

3.1. Analysis of the nature and distribution of thunderstorms with the main observation time

Over the 20-year period, a total of 328 days with thunderstorms were recorded across the two stations for the period (2000-2019). Baghdad Airport, experienced the highest frequency 199 days, and Basra Airport, had the lowest frequency 129 days. Figure 2, shows that the number of thunderstorms fluctuated significantly from year to year, without exhibiting a clear long-term trend of increase or decrease. This fluctuation reflects the changing nature of the meteorological factors influencing the formation of thunderstorms, which are directly related to the dynamic and thermal conditions of the atmosphere in the region. The total number of annual thunderstorm days varied widely during the study period, with a minimum value of 4 days (in 2005) for Baghdad Airport station and 2 days (in 2005, 2009 and 2012) for Basra Airport station, which may reflect relative atmospheric stability and a decrease in atmospheric humidity or a weakness in the development of cumulonimbus clouds, and a maximum value of 20 days (in 2002 and 2018) for Baghdad airport station and 13 days (in 2003 and 2018) for Basra Airport station. The period from 2007 to 2017 was relatively more stable. The period (2018-2019) recorded a second peak similar to 2002 at Baghdad Airport station, reaching 20 days in 2018, indicating exceptional thunderstorm activity that may be related to unusual climatic conditions such as increased atmospheric instability or high peak convection (CAPE) values. This was followed by a rapid decline to 7 days in 2019. The presence of peaks in 2002 and 2018 indicates a significant influence of regional and local weather conditions occurring in irregular cycles. This variability is a critical factor to to be considered when assessing extreme weather risks and infrastructure planning and requires deeper statistical analysis to link these cycles to larger-scale climate factors (such as climate oscillations or the El Niño/La Niña phenomenon). However, continued monitoring and analysis of thunderstorm data over longer timescales, and linking them to factors such as surface humidity, lower atmosphere temperatures, and atmospheric pressure distribution, may help clarify future trends in thunderstorm activity in the region. In 2005 and 2008, we experienced the fewest thunderstorms, while conversely, we witnessed the highest number of dust storms in Baghdad. The increased concentration of dust (particulate matter 2.5) in the atmosphere is due to the low relative humidity (dry thunderstorms) with the passage of a cold front (of high density), which stirs up the dust and causes it to remain suspended for a period of time. At the observational level, a positive correlation is observed between thunderstorm activity (frequency or intensity) and atmospheric PM2.5 concentrations above the surface. This is because thunderstorms stir up aerosols (during the storm), redistribute pollutants, and generate aerosol particles at high altitudes. Thunderstorms are also associated with local sources of dust and smoke (such as fires or construction dust), which can be exacerbated by the storm's atmospheric conditions.

However, this relationship is not universal and can be ambiguous: Thunderstorms accompanied by rain clear the air of particles, which may lead to a decrease in PM2.5 under certain conditions, with the decrease continuing after the storm. This depends on the region, the season, and the sources of pollution.

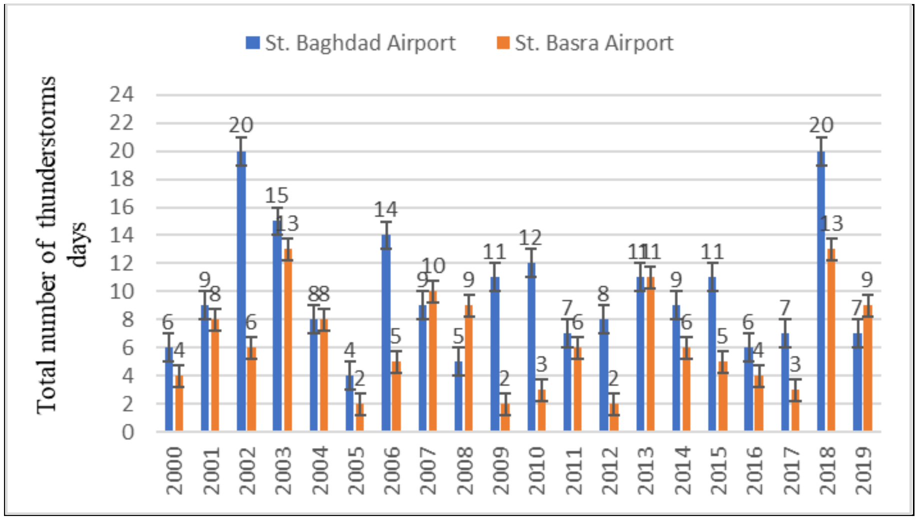

Figure 2. Thunderstorms distribution per year, 2000-2019.

An analysis of the monthly average of the number of days with thunderstorms for the period 2000 to 2019 (January, February, March, April, May, September, October, November, and December) at the two stations showed that the maximum frequency of thunderstorm activity (64.03%) occurs in spring (April), but it occurs in autumn (October) for the Baghdad Airport station (16.08%). Analysis reveals a pronounced seasonal variation, with the majority of thunderstorms occurring in the spring [23]. Notably, peak activity is observed in April (See Figuer 3). During the spring peak period (the main peak), the highest levels of thunderstorm frequency occur in spring, specifically in April, which recorded the highest total value ever at 103 days. These conditions are typically attributed to the strong interaction between advancing warm, humid air masses and unstable atmospheric systems between high and low latitudes. These conditions lead to enhanced convection and the formation of cumulonimbus clouds, which are responsible for thunderstorms. The autumnal peak (secondary peak) occurs in the fall as the thermal effect begins to recede and low-pressure systems return to the region. October (32 days) for the Baghdad Airport station, followed by November (19 days) for the Basra Airport station. In contrast, in summer, it did not record any thunderstorm events. A clear decrease in the frequency of storms was observed during September, being the least active month, with approximately 4 storms recorded at two stations. This is attributed to the dominance of subtropical highs in the summer months; stabilizing the atmosphere and preventing the development of cumulus clouds. In winter, thunderstorms occur at rates ranging from 16 to 6, reflecting the presence of some instability (poor) associated with the cold fronts of mid-latitude lows. This distribution indicates that seasonal dynamics and thermal factors play the most important role in determining the pattern of thunder activity in Baghdad, as spring is the most suitable period for storms to occur as a result of high surface temperatures, increased relative humidity, and the effectiveness of convection. The monthly distribution also shows a general consistency with the arid climate patterns of the region, where the transitional seasons are characterized by more frequent weather disturbances compared to the stable seasons (summer and winter).

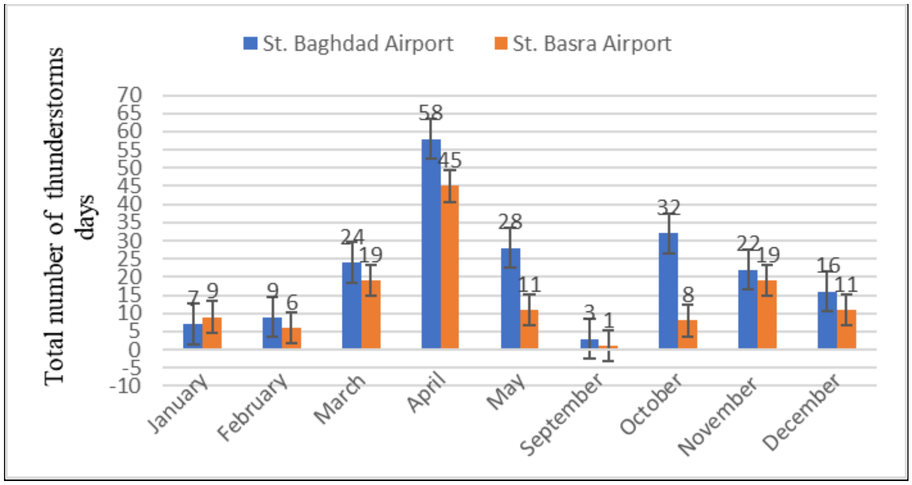

Figure 3. Thunderstorms distribution per month, 2000-2019.

Table 6, shows the values of the air stability index which is classified into five categories. The most occurrence values of K index were under "26 – 30" category for Baghdad Airport station which represent widely scattered thunderstorms. For Basra Airport station the most repeatable values for K index were under "31–35" category which refers to scattered thunderstorms. This suggests that the atmospheric environment during the studied period was primarily characterized by conditions that were conducive to the development of moderate and intense convection. This is consistent with the study area's climatic characteristics, that include frequent heat waves and periods of high relative humidity in the lower layers, creating favorable conditions for vertical instability. Was analyzed nine months of data for Baghdad Airport and Basra Airport stations; the results showed that the best time for thunderstorms to recur is 18:00 UTC. The lowest time for thunderstorms at Baghdad Airport station is 06:00 UTC, while at Basra Airport station it is 00:00 UTC.

Table 6. Frequency of air stability index (2000-2019).

Stations	**K below 20**	**K between 20 to 25**	**K between 26 to 30**	**K between 31 to 35**	**K = 40 or Above 35**	**Total frequency (cases)**
St. Baghdad Airport	23	55	82	70	9	239
St. Basra Airport	29	23	45	60	11	168

3.2. Analysis of PM2.5 concentration associated with thunderstorms

Results of the impact of thunderstorm on PM2.5 concentration and their frequencies are presented in Figures 4 and 5 and summarized in Table 7. These results are based on PM2.5 concentrations before, during, and after the thunderstorms at Baghdad Airport and Basra Airport stations, and by using hourly data of thunderstorm (wet and dry) for nine months, for the period from 2000 to 2019. Figure 4 shows that the concentration of PM2.5 is at three levels: (B), (C), and (D) groups in varying proportions. The reason is the lack of high humidity in the air (according to the Iraqi Meteorological Organization). Another reason is the result of the wind bringing dust from western Iraq (the desert), and there are millions of cars and a large population in Baghdad, in addition to urban development and the bulldozing or death of agricultural land due to drought and lack of rain. Therefore, the concentration has not decreased. Baghdad Airport station:

- Before 1h of thunderstorm: The majority of PM2.5 frequencies fall within the (C) (35.5-55.4 μg/m³) and (D) (55.5-150.4 μg/m³) ranges. A significant number of frequencies also fall into the (B) category (35.5-55.4 μg/m³), with a very small frequency of (E) (150.5-250.4 μg/m³) air.
- During of thunderstorm: There is a slight decrease (varying proportions) in the frequency of PM2.5 in the (D) (prevailing frequency) and (B) range. The frequency of the (C) category appears to increase, with a very small frequency of (E) (150.5-250.4 μg/m³) and (F) (250.5-500.4 μg/m³) air.
- After 1h of thunderstorm: We observe a continued increase in PM2.5 frequency in the (B) range, with a decrease in PM2.5 frequency in the (C and D) ranges, and observed a very small frequency of (A) (0-12 μg/m³) and (E) (150.5-250.4 μg/m³). This indicates no significant change in PM2.5 after the storm, because most cases recorded light rain or no rain (dry thunderstorm).

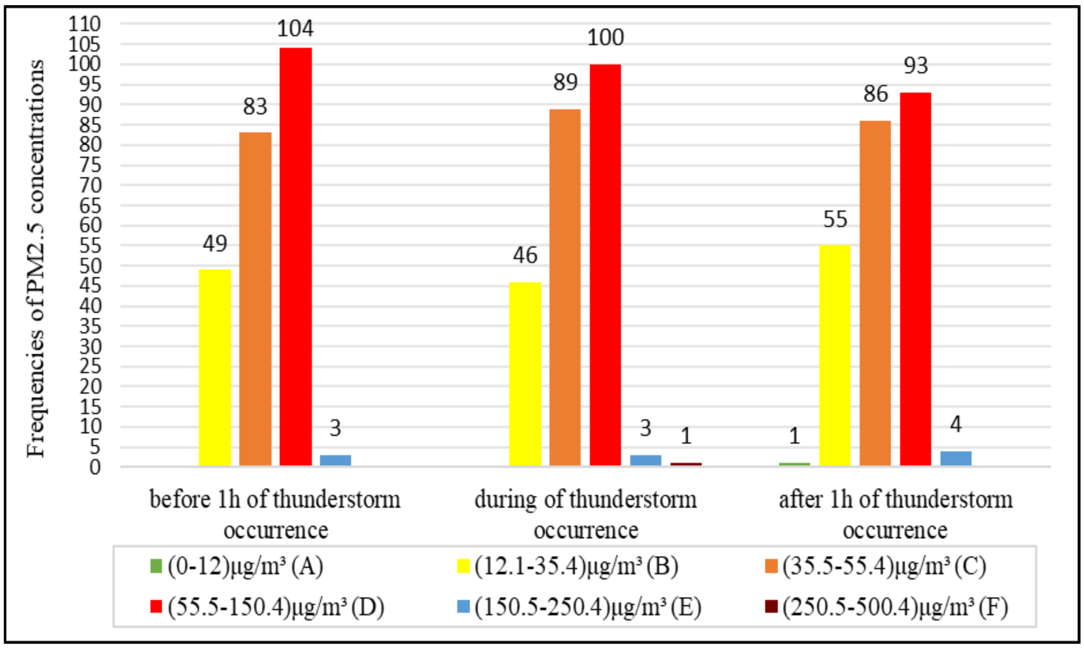

Figure 4. Temporal analysis of air quality status: Mean frequencies of PM2.5 concentration levels (2000-2019) for Baghdad Airport station.

Figure 5 shows that the concentration of PM2.5 recorded (D) levels approximately 42% of thunderstorm frequency. In recent years, high concentrations of air pollution have been recorded as a result of waste incineration and destruction of green spaces, estimated at 10-15% (unlike in the nineties, there were many green spaces here), and this city is characterized by a large number of oil wells (it is considered the first oil field in Iraq), as well as millions of vehicles running on fuel. Since 2003, the number of people who have cancer and other diseases has reached an all-time high. According to previous studies, the wind direction accompanying storms is predominantly north and northwest. Basra Airport station:

- Before 1h of thunderstorm: The majority of PM2.5 frequencies fall within the (C) (35.5-55.4 μg/m³) and (D) (55.5-150.4 μg/m³) categories. A moderate number of frequencies also fall into the (B) (12.1-35.4 μg/m³) range, with a small frequency of (E) (150.5-250.4 μg/m³) air and a very small frequency of (A) and (F).
- During of thunderstorm: There is a slight increase in the frequency of PM2.5 in the (B) range. The frequency of the (D) (prevailing frequency) and (E) ranges appears to be steadfast, but the observed category (C) appears to decrease.

- After 1h of thunderstorm: we observe a continued increase in the frequency of PM2.5 in the (C) and (E) ranges, with a decrease in frequencies in the (B) category, and with a constant frequency of the (A) and (D) categories. Indicating that even if there is a thunderstorm, it is light rain or no rain (dry thunderstorm). The concentration of category (A) for the two stations during the study period was very low, with high concentrations of the remaining pollutant and hazardous categories. The reason is the weak rainfall resulting from the low relative humidity in the atmosphere, and therefore no change occurred in the decrease of concentrations that are dangerous to human life.

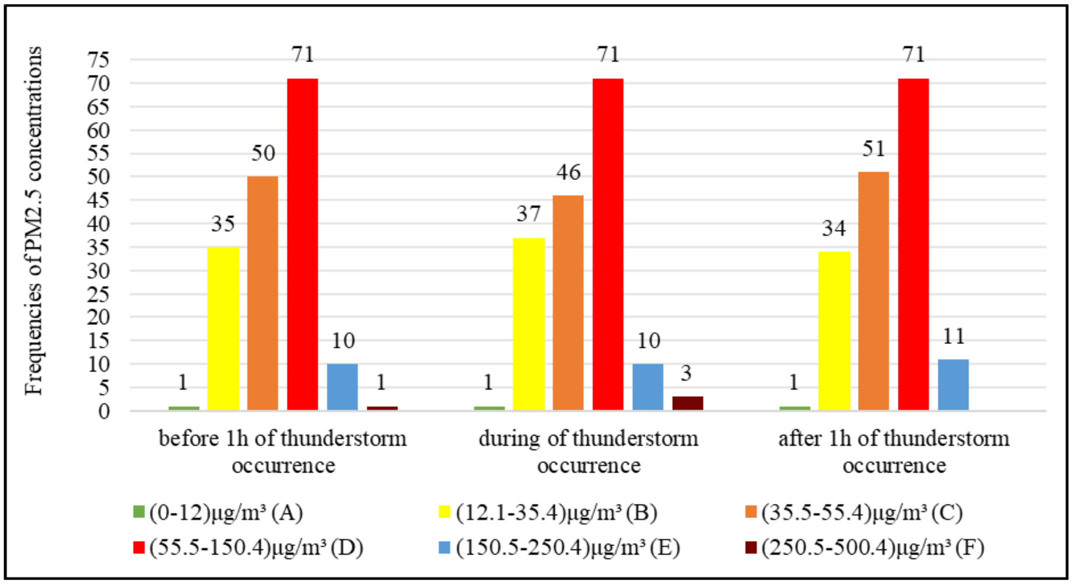

Figure 5. Temporal analysis of air quality status: Mean frequencies of PM2.5 concentration levels (2000-2019) for Basra Airport station.

Table 7. Summarizes the results (thunderstorms and PM2.5) for three meteorological stations for the period (2000-2019).

Station	Thunderstorm Days	Total Thunderstorm Events	Events with Rain	Events no Rain	Highest rate PM2.5 before 1h	Highest rate PM2.5 during 1h	Highest rate PM2.5 after 1h	Sources of Pollution
Baghdad Airport	199 days	239 cases	111 cases	128 cases	(D)	(D)	(D)	Petrochemical Plant, Oil Refinery, Power plant, Brick
Basra Airport	129 days	168 cases	63 cases	105 cases	(D)	(D)	(D)	Petrochemical plant, Oil Refinery, Oil Wells, Power plant, Brick and Asphalt factory, Food factory, Steel and Iron foundry, waste incineration, agricultural land removal, burning of crude oil and gas, vehicle exhausts.

From the table, one can note that the frequency of days of thunderstorms and rain (cases) decreases from north to south, while the highest concentration of PM2.5 is from south to north. This indicates that the increase in rainfall leads to a decrease in concentrations of PM2.5. Emissions from brick factories are responsible for 15% of air pollution in Baghdad (Ministry of Environment Report for 2023).

The first reason is caused by car exhausts, which reached 40% (the number of cars in Baghdad for 2023 is almost 3 million), and the second reason is emissions from civilian power generators due to government power outages, which also reached 40%.

3.3. NDDI map Analysis

NDDI was calculated and analyzed based on Table 5 for Baghdad and Basra cities. The results are presented in figure 6 and 7. A comparative analysis of NDDI maps for Baghdad and Basra reveals a notable increase in the severity of dust events during the period (2000-2019). Figure 6 shows a significant escalation in dust intensity, indicating a prevalence of moderate dust concentrations, primarily represented by the yellow pattern (NDDI 0.20-0.30). The emergence of orange pixels indicates that dust concentrations have frequently exceeded the 0.30 threshold, corresponding to high dust events. These intense dust conditions are particularly evident in the northern and southern parts of the mapped area. This suggests a marked deterioration in air quality conditions related to dust over the past decade. Also, in the absence of the red-color category (NDDI > 0.40), a strong decrease was observed in the green-shaded areas (NDDI ≤ 0.10) with minimal dust, particularly along the Tigris River, where vegetation or water bodies likely act as a natural dust suppressant. Figure 7 also shows a significant escalation in dust intensity; the dominant yellow and orange patterns persist (moderate to high dust concentrations). The emergence of orange pixels indicates that dust concentrations have frequently exceeded the 0.30 threshold, corresponding to high dust events. These intense dust conditions are particularly evident in the western, southwestern, and northeastern parts of the mapped area. This suggests a marked deterioration in air quality conditions related to dust over the past decades. Also, in the absence of the red-color category (NDDI > 0.40). Green shaded areas (NDDI ≤ 0.10) with minimal dust in the mapped area but at a very low level are observed, particularly along the Euphrates and Tigris Rivers, where vegetation or water bodies likely act as a natural dust suppressant. There is a positive relationship between dust intensity and the Normalized Difference Dust Index; see Table 5. Thus, there is an increase in the frequency and intensity of dust events in Basra. The shift from a landscape dominated by low and moderate dust to one that includes severe dust events points to a concerning trend, likely influenced by environmental factors such as desertification and land-use changes. Iraqi cities, like Baghdad and Basra, suffer from severe air pollution, with various sources, such as vehicle exhaust and power plants, releasing hazardous pollutants. The primary source of this pollution is the burning of oil and natural gas. In addition, urban areas in Iraq face significant environmental challenges, ranging from air pollution to the effects of climate change, such as extreme heat, low humidity, scarce rainfall, and water shortages that lead to drought and desertification. Furthermore, soil salinization and water pollution threaten to degrade essential ecosystems. The increased frequency of dust storms, especially in the summer, is due to dry conditions, a lack of rainfall, limited vegetation, and high solar temperatures, which lead to soil disintegration and instability. In contrast, their frequency decreases in the winter. If the situation of increasing dust storms continues without solving the problem, during the next 10 years the orange areas expect to turn red, and this is dangerous to human health, especially for those who suffer from heart, vascular, respiratory, and eye diseases.

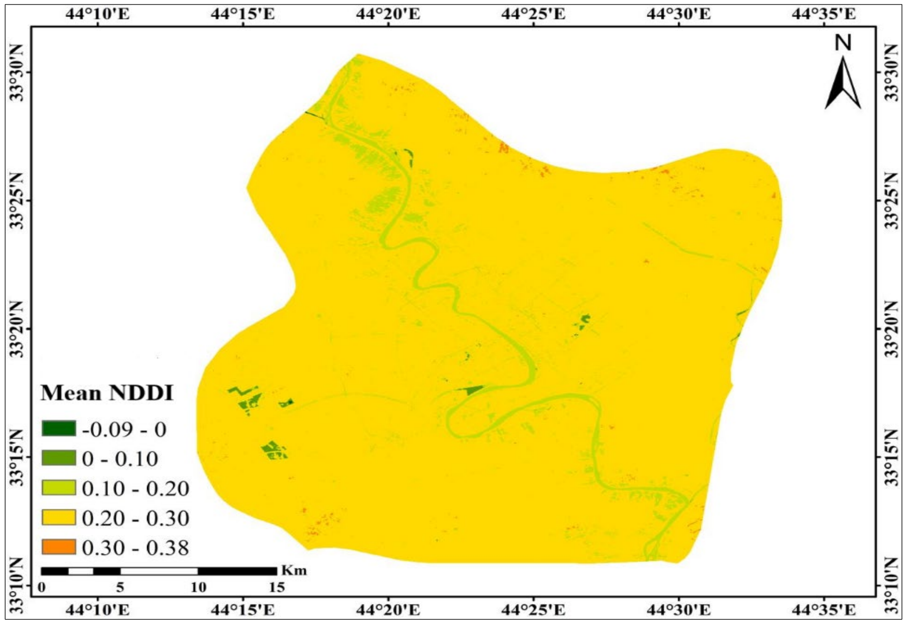

Figure 6. Annual average annual NDDI map, classified by five levels of dust intensity in Baghdad (2000-2019).

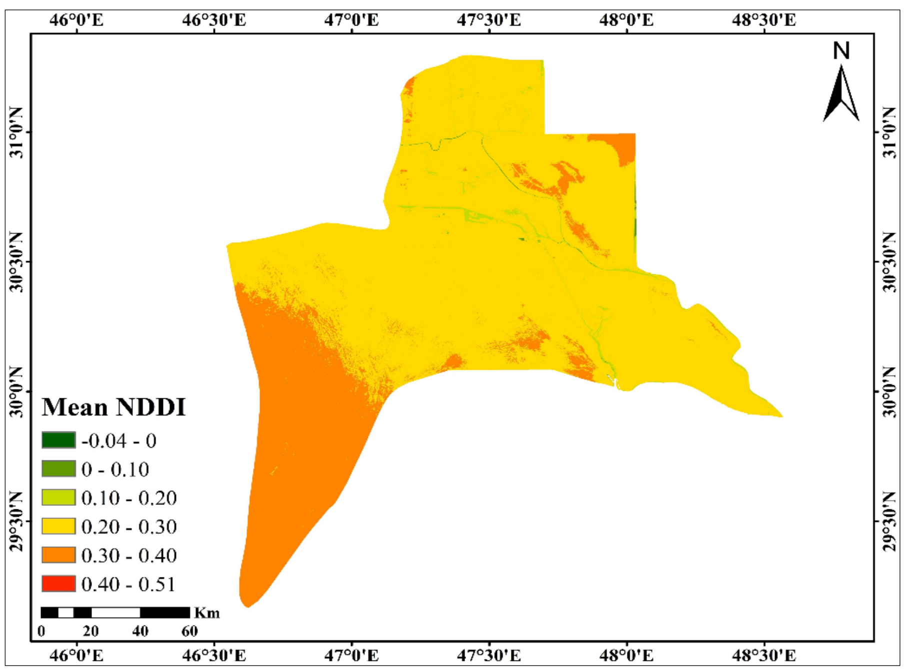

Figure 7. Annual average annual NDDI map, classified by six levels of dust intensity in Basra (2000-2019).

4. Conclusions

Based on the Analysis of the frequency of thunderstorms in the study area, it can be concluded that:

The highest frequency of thunderstorms In Iraq, the highset frequency of thunderstorms occurs in Spring and Autumn. The highest month for Baghdad Airport and Basra Airport stations was April (58 and 45 days, respectively). The highest annual frequency of thunderstorms was for Baghdad Airport station in 2018 and 2002 (20 days) and Basra Airport station in 2003 and 2018 (13 days). The highest value for the number of days of thunderstorm recurrence at Baghdad Airport station was 8 days, which occurred in April 2002, while at Basra Airport it was 7 days in April 2003 and 2007.

The most occurring values of the K-index were under the “26–30” category for the Baghdad Airport station, while for the Basra Airport station, the most repeatable values of the K-index were under the “31–35” category. Both Baghdad and Basra Airport station recorded the highest concentration of PM2.5 (D) particulates before, during, and after the thunderstorm. The concentration of air pollution is without permissible level. From the NDDI index for Baghdad for the period (2000-2019), it is not a dangerous indicator, while for Basra at the same period of time, it is a dangerous indicator. The data shows a direct relationship between thunderstorms and PM2.5 particles on the surface during and after the storm, over a certain period of time. However, there is an inverse relationship between thunderstorms and dust or sandstorms during the weak rainy season (non-rain-bearing thunderstorms), particularly in Basra.

Supplementary Materials: None

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