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Spatio-Temporal Dynamics of Air Pollution in Hyderabad: Geostatistical Interpolation and Trend Analysis

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Abstract:
Introduction: The rapid transformation of the world is being driven by urbanization, a major force reshaping society (United Nations, 2018). As more and more people move from rural areas to urban centres, societies are changing. This dramatic population shift not only alters the demographics of societies but also triggers profound societal and environmental consequences. Air pollution is one of them, and it's a major global health crisis, silently harming millions of people worldwide (World Health Organization, 2021). This study aims to study the dynamics of air pollution in Greater Hyderabad Municipal Corporation using the AQI data
Methods: This study investigated the spatio-temporal dynamics of air quality in Hyderabad from 2016 to 2023, utilizing geostatistical interpolation techniques—IDW, Spline, and Kriging—applied to the Air Quality Index (AQI). Secondary monthly AQI data, along with specific pollutant concentrations (PM2.5, PM10, NO2, and SO2), were obtained from the Telangana State Pollution Control Board and the Central Pollution Control Board-Delhi, sourced from the National Air Quality Monitoring Programme.
Results: The spatial variation, consistently highlighted by all three methods, suggests a strong correlation between urban density, industrial activities, and heightened pollution levels within the city's core, underscoring the imperative for targeted interventions in central and eastern Hyderabad to mitigate air pollution and enhance public health.
Conclusion: The consistent identification of central Hyderabad as a pollution hotspot underscores the urgent need for targeted pollution mitigation strategies in this area. The observed spatial disparities in air quality raise environmental justice concerns, highlighting the differential exposure to pollution in different parts of the city. The congruence between the tabular data and the consistent results of all three methods, confirms the efficacy of these interpolation techniques in accurately representing the spatial patterns of air pollution in Hyderabad. The results show the importance of urban planning in rapidly developing cities, to reduce the amount of pollution that is produced. Seasonal trends, such as the increased pollution in the winter months, must be considered when creating pollution mitigation strategies.

Keywords: Air pollution, AQI, Spatio- temporal analysis, Kriging, IDW, Spline,

1. Introduction:

The rapid transformation of the world is being driven by urbanization, a major force reshaping society (United Nations, 2018). As more and more people move from rural areas to urban centres, societies are changing. This dramatic population shift not only alters the demographics of societies but also triggers profound societal and environmental consequences. Air pollution is one of them, and it's a major global health crisis, silently harming millions of people worldwide (World Health Organization, 2021). Hyderabad, the state's most populous and urbanized city, is likely to play a significant role in addressing the needs of this growing senior population. Hyderabad, the capital of Telangana, has grown from an indigenous city to a colonial city to an information technology superpower; Hyderabad has experienced tremendous physical change over time (Alam, 2004). Rapid urbanization, increased vehicular traffic, and industrial activities have contributed to deteriorating air quality in this metropolitan city (Gurjar et al., 2016; Guttikunda & Jawahar, 2014; Nagendra et al., 2004). Exposure to air pollutants can lead to a wide range of health problems, from mild respiratory irritation to severe conditions like asthma, lung diseases, and even cancer (Pope & Dockery, 2006). The long-term effects of air pollution can be devastating, making it a silent killer that undermines public health (Ghosh & Guttikunda, 2020). The present study examines the dynamics of air pollution in Hyderabad city, using the geospatial techniques. These techniques provide different approaches to estimating pollutant concentrations at unmonitored locations and analysing the spatial characteristics of air quality. The application of such approaches is necessary to properly grasp and forecast the behavior of environmental systems under rising stress since the growing anthropogenic impact on the environment and the need of optimal environmental management techniques demand (Goovaerts, 2018). Indeed, the complexity of spatial fluctuations displayed by environmental pollutants, especially in fast developing areas, highlights even more the vital need of geostatistical methods in precisely characterizing and mapping pollution extents (Ijerph special issue, n.d.).

1.1 Definition: The World Health Organisation defines air pollution as any chemical, physical, or biological factor altering the natural properties of the atmosphere, therefore contaminating either an interior or outdoor environment.

1.2 Types of Air pollutants:

Directly emitted into the environment from sources like cars, businesses, and natural processes, these are primary pollutants. For instance, carbon monoxide (CO), sulphur dioxide (SO_2), nitrogen oxides (NO_x), particulate matter (PM), volatile organic compounds (VOCs), and lead (Pb). Secondary pollution results from chemical interactions between main contaminants in the atmosphere. Ozone (O_3), sulfuric acid (H_2SO_4), nitric acid (HNO_3), smog, and peroxyacetyl nitrates (PANs) among other things.

2. Literature reviews:

Low- and middle-income nations often struggle to monitor air pollution properly. The growing frequency of automobiles feeds higher usage of fuels like petrol, which increases carbon dioxide (CO2) and fine particulate matter (PM2.5) emissions into the air. One main reason air quality is declining is this increase in emissions. Geographic Information Systems (GIS) were shown by Charlot et al. (2002) to be useful in environmental contamination study. GIS, they clarified, is a computerized system that helps to gather, model, process, retrieve, analyze, and display data related to sites.

Pollution models built within GIS platforms can identify areas with high pollution levels, classify populations at risk, and support epidemiological investigations. Studies using GIS employ a comprehensive, integrated methodology that considers various factors, such as vehicle emissions, to understand pollution patterns. Data collection and generation is highly desirable to estimate/predict the required pollutant (Boznar, Lesjak, & Mlakar, 1993). Moreover, high demand for urban air quality estimation models, which help in calculating pollutant concentration at a desired discrete location is present (Hurley, Physick, & Luhar, 2005). Local geography and the various meteorological factors such as wind speed, pressure, temperature, precipitation in the control volume enclosed by the atmospheric boundary layer, have a contrasting effect on pollutant estimation (Baklanov, Korsholm, Mahura, Petersen, & Gross, 2008). Nevertheless, it is not possible to consider the synergic effect of all such factors during physical modelling. Hence, pollutant data across India from Nationwide Ambient Air Quality Monitoring Network (NAAQM) program is relied upon. Moreover, the dispersion of these pollutants, rather randomly in the lower layer of the atmosphere also introduces a varying degree of uncertainty (Mallet & Sportisse, 2008). The spatial and temporal distribution of the pollutants can be estimated using multiple basic laws of physical sciences such as equations of mass, energy, momentum conservation; but in addition to gas laws and thermodynamic parameters, one requires multiple boundary conditions at each grid boundary. In recent studies, kriging-based regression model has been used to quantify the radioactive soil contamination. Kriging based techniques have been used in structural analyses, specifically to analyse Timoshenko beams where conventional polynomial interpolation was usually used (Wong, Sulistio, & Syamsoeyadi, 2018). Monte Carlo Techniques combined with Kriging have used for Reliability Analysis of Mechanical System Models. It has helped to overcome specific drawbacks of using small failure probabilities (Lelièvre, Beaurepaire, Mattrand, & Gayton, 2018). In a recent study in Central Italy, Kriging based regression model was used to quantify the geogenic radon potential and subsequent exposure risk from the contaminated soil (Giustini, Ciotoli, Rinaldini, Ruggiero, & Voltaggio, 2019). Ordinary Kriging, Regression Kriging and Co-Kriging were used to map potentially toxic metal concentrations in Southern China (Xu et al., 2019). Metrological parameters such as wind speed are profoundly affected by the terrain of a site and these methods have also been previously modelled in various studies using unadorned methods such as IDW (Palomino & Martin, 1995). Earlier studies with spatial interpolation have observed significantly smaller errors when there are limited topographical variations across the study area. It has been seen during the assessment of parameters such as ambient temperature with spatial interpolation that, in case of mountainous region – the yielded errors are large in magnitude when compared to plain or rolling terrain (Chung & Yun, 2004; Kumari, Basistha, Bakimchandra, & Singh, 2016). The capacity of Geostatistics to quantify the spatial distribution of pollutants, refine spatial estimates, and effectively characterize pollution risks renders it an indispensable tool for the formulation of targeted environmental action strategies and informed public health policies (IJERPH Special Issue, n.d.) These techniques can also be combined with data from low-cost sensors to improve monitoring networks worldwide (Dünnebeil, Marjanović, & Žarko, 2017)

Table 1: Air Pollutants Studied Using Geostatistical Methods

Air Pollutant	Geostatistical Method(s) Used	Example Study/Reference	Key Finding(s)
PM10	Ordinary Kriging, Spatio-	Goovaerts, P. (2018). Geostatistical analysis methods for estimation of environmental pollution: A review. *International Journal of Environmental Research and Public Health*	Mixed performance for OK, spatio-

	temporal Kriging	, *15*(6), 1214. https://doi.org/10.3390/ijerph15061214	temporal captures variations
PM2.5	Ordinary Kriging, Universal Kriging, Spatio-temporal IDW, Modified IDW	Kim, H., & Lim, H. (2018). Geostatistical analysis of mobile source emissions: A South Carolina case study. *Journal of the Air & Waste Management Association* , *68*(8), 868-882. https://doi.org/10.1080/10962247.2018.1462060	Kriging often outperforms IDW, modifications improve IDW
NO2	Universal Bayesian Kriging, Cubic Splines	Cameletti, M., Pirani, M., & Ignaccolo, R. (2018). A Bayesian kriging model for estimating residential exposure to air pollution of children living in a high-risk area in Italy. *Geospatial Health*, *13*(2), 674. https://doi.org/10.4081/gh.2018.674	Bayesian kriging incorporates covariates, splines model dose-response
SO2	Universal Bayesian Kriging	Cameletti, M., Pirani, M., & Ignaccolo, R. (2018). A Bayesian kriging model for estimating residential exposure to air pollution of children living in a high-risk area in Italy. *Geospatial Health*, *13*(2), 674. https://doi.org/10.4081/gh.2018.674	Bayesian kriging estimates residential exposure
O3	Ordinary Kriging	Kim, H., & Lim, H. (2018). Geostatistical analysis of mobile source emissions: A South Carolina case study. *Journal of the Air & Waste Management Association*, *68*(8), 868-882. https://doi.org/10.1080/10962247.2018.1462060	Kriging used to analyze spatial variability
VOCs	Kriging	Alonso, L., Sánchez, M. L., & Fernández, J. R. (2023). Analysis of air pollutants for a small paintshop by means of a mobile platform and geostatistical methods. *Applied Sciences*, *16*(23), 7716. https://doi.org/10.3390/app16237716	Kriging used with UAV data for spatial analysis
Smoke	Kriging	Bayraktar, H., & Turalioglu, F. S. (2005). A Kriging-based approach for locating a sampling site - In the assessment of air quality. *Stochastic*	Kriging used for sampling site selection

		Environmental Research and Risk Assessment, *19*(4), 301-305.	
AQI	Spline Methods, IDW	Li, Y., & Chen, L. (2019). Comparative study of the spatial interpolation methods for the air quality assessment. In *Remote Sensing and Geographic Information System (RSGIS) for Environment and Disaster Monitoring, Modeling, and Simulation XIX* (Vol. 11175, p. 111750B). SPIE. https://doi.org/10.1117/12.2320402	Splines can be optimal, IDW visualizes intensity

3. Objectives:

- Spatio-Temporal Analysis of Key Air Pollutant Concentrations in residential, commercial, and industrial areas of Hyderabad.
- Geostatistical Modeling and Trend Analysis of Air Quality Index (AQI) to Identify High-Exposure Zones.
- Development of Evidence-Based Intervention Strategies for Air Pollution Mitigation and Health Impact Reduction in Hyderabad.

4. Methodology for Annual AQI Analysis:

To analyse the annual air quality patterns at each monitoring station in Hyderabad, the average annual AQI was calculated. This was achieved by calculating the arithmetic mean of the monthly AQI values for each station and dividing by 12, as represented by the following formula:

$$Average\ Annual\ AQIs = \frac{\sum_{m=1}^{12} AQIs,m}{12}$$

Where:

- *Average Annual AQIsis the average annual AQI for station s.*
- $\frac{\sum_{m=1}^{12} AQIs,m}{12}$ *Is the sum of the AQI values for each month (m) from 1 to 12 at station s.*
- *12 is the number of months in a year.*

4.1 Study area:

To study Spatio-Temporal Dynamics of Air Pollution in Hyderabad, secondary data of 4 pararameters ($PM_{2.5}$, PM_{10}, NO_2, SO_2) has been collected from 10 monitoring stations (Balanagar, Tarnaka, Nacharam, Abids, Uppal, Jublee Hills, Paradise, Charminar, Zoo Park, Jeedimetla) of GHMC. For the Geostatistical Interpolation and Trend Analysis AQI data of 19 Monitoring locations of GHMC has been taken. All these has been located in the Thematical map of interpolation methods. Data from the 2023 World Air Quality report indicates a marginal improvement in Hyderabad's air quality, with the annual average PM2.5 concentration decreasing to 39.9 µg/cubic meter from 42.4 µg/cubic meter in 2022. However, despite this slight reduction, both $PM_{2.5}$ and PM_{10} concentrations in the city remain significantly higher than the guidelines set by the World Health Organisation (WHO) and the Government of India

Map illustrating Study area:

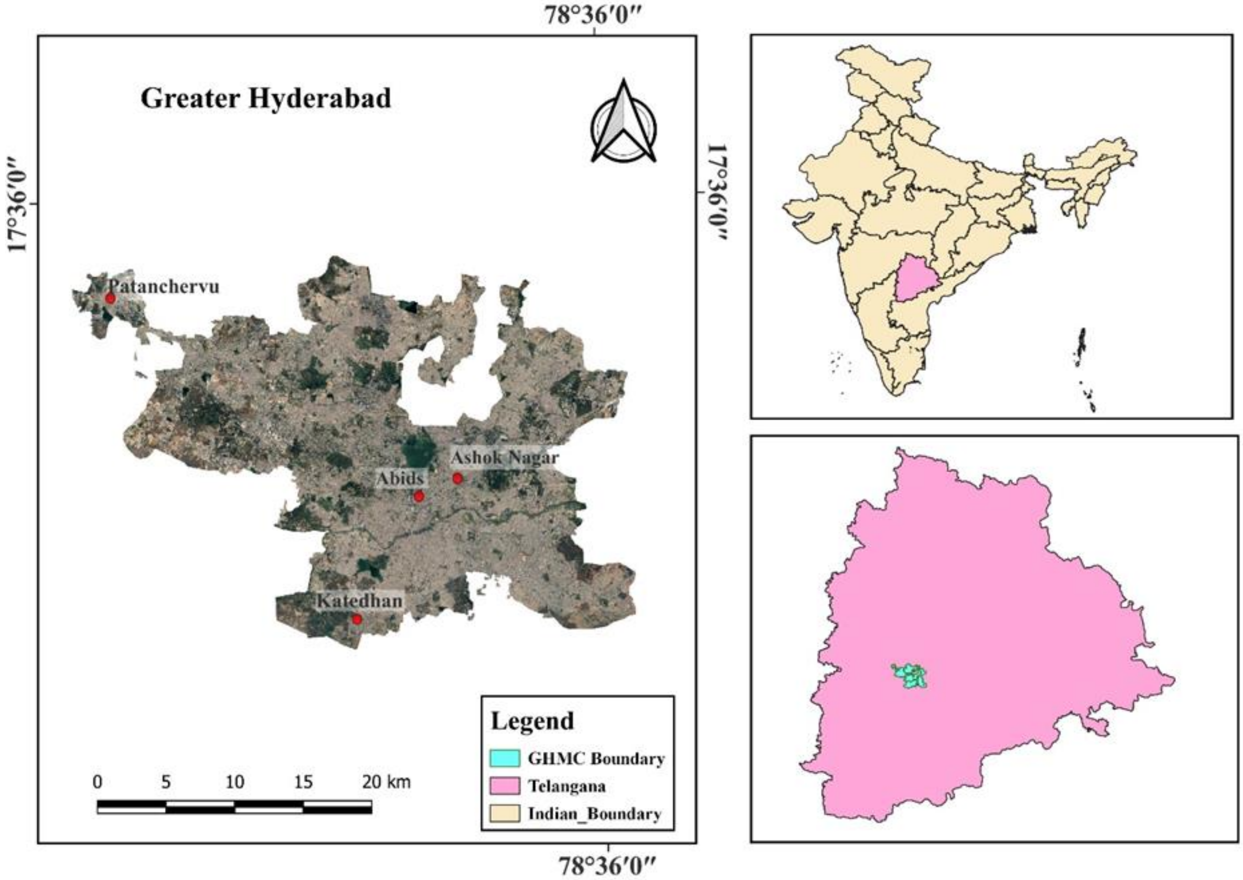


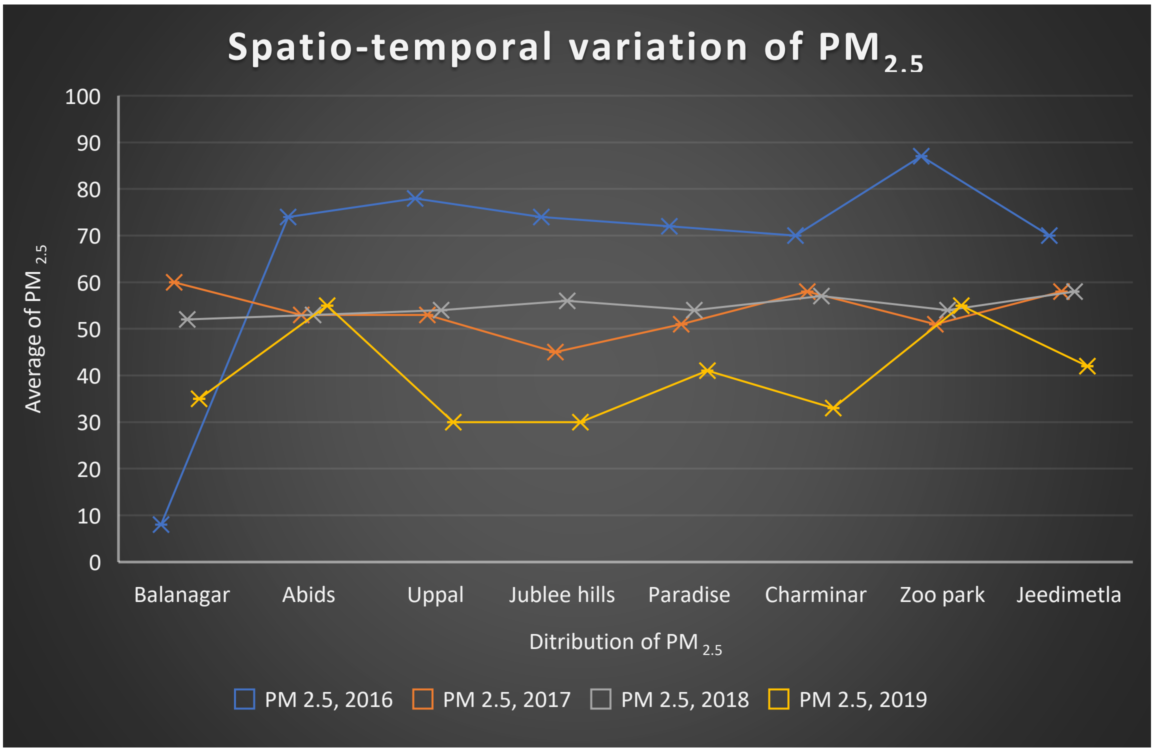
Figure.1: Map showing the study area

5. Spatio-Temporal Dynamics of Air Pollution in Hyderabad:

Table 1: Annual average of $PM_{2.5}$ data in GHMC

Location	PM 2.5, 2016	PM 2.5, 2017	PM 2.5, 2018	PM 2.5, 2019
Balanagar	8	60	52	35
Abids	74	53	53	55
Uppal	78	53	54	30
Jublee hills	74	45	56	30
Paradise	72	51	54	41
Charminar	70	58	57	33
Zoo park	87	51	54	55
Jeedimetla	70	58	58	42

Source: NAMP



Graph 1: shows the Spatio-temporal variation of $PM_{2.5}$

5.1 Analysis: The graph 1 depicts the spatio-temporal variation of PM2.5 (particulate matter with a diameter of 2.5 micrometres or less) across eight locations in Hyderabad, Telangana, India, over four years (2016-2019).

Significant Spatial Variation: There is a clear difference in PM2.5 levels across the various locations. Zoo park consistently shows the highest PM2.5 levels throughout the four years. Balanagar shows the lowest PM2.5 levels in 2016, with a drastic increase in 2017. Abids, Uppal, Jubilee Hills, Paradise, Charminar and Jeedimetla show relatively similar PM2.5 averages throughout the 4 years.

Temporal Trends: PM2.5 readings in Hyderabad showed clear variances depending on location between 2016 and 2019. Balanagar began 2016 with low levels; Abids experienced a quick rise; other sites had a consistent average. 2017 offered notable swings; Balanagar had a big increase while Uppal dropped considerably. While Charminar saw a little rise, 2018 exhibited relative constancy throughout the city. Except for a notable rise in PM2.5 readings at Zoo Park, this constancy persisted throughout 2019, underscoring the localized character of pollution changes inside the city.

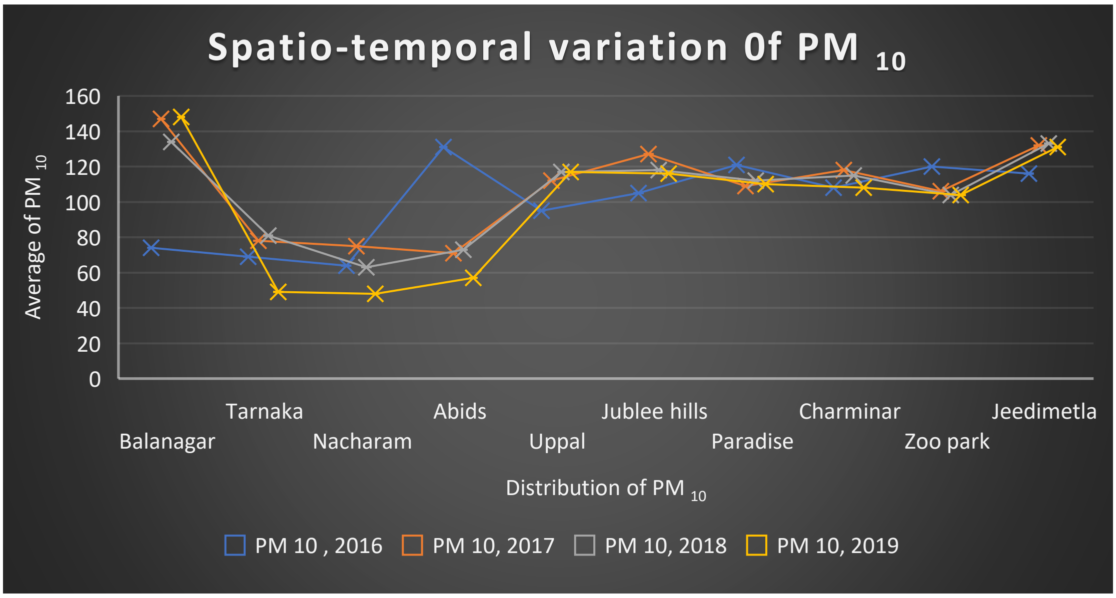
Zoo Park Anomaly: The Zoo park consistently exhibits significantly higher PM2.5 levels compared to all other locations across all four years. This indicates a potential localized source of PM2.5 pollution in that area.

Table 2: Annual average of PM_{10} data in GHMC

Location	PM_{10}, 2016	PM_{10}, 2017	PM_{10}, 2018	PM_{10}, 2019
Balanagar	74	147	134	148
Tarnaka	69	78	81	49
Nacharam	64	75	63	48

Abids	131	71	73	57
Uppal	95	112	117	117
Jublee hills	105	127	118	116
Paradise	121	109	112	110
Charminar	108	118	115	108
Zoo park	120	106	104	104
Jeedimetla	116	132	133	131

Source: NAMP



Graph 2: shows the Spatio-temporal variation of PM_{10}

5.2 Analysis: The graph 2 depicts the spatio-temporal variation of PM10 (particulate matter with a diameter of 10 micrometres or less) across ten different locations in Hyderabad over four years (2016-2019).

Significant Spatial Variation: There are noticeable differences in PM10 levels across the locations. Balanagar and Jeedimetla consistently show high PM10 levels throughout the period. Tarnaka and Nacharam show relatively low PM10 levels, particularly in 2017 and 2018. Abids displays a significant spike in PM10 levels in 2017.

Temporal Trends: In 2016 PM10 levels were high at Balanagar and Jeedimetla, and then dropped off at Tarnaka and Nacharam. The levels then rise again at Abids, and stay relatively consistent at the rest of the locations. In 2017 A large spike of PM10 is seen in Abids, and a large drop in PM10 is seen in Tarnaka and Nacharam. In 2018: The levels of PM10 are relatively consistent across all locations, but the levels are still fairly low at Tarnaka and Nacharam. In 2019 The levels of PM10 are again high at Balanagar and Jeedimetla, and the levels are increasing at the other locations.

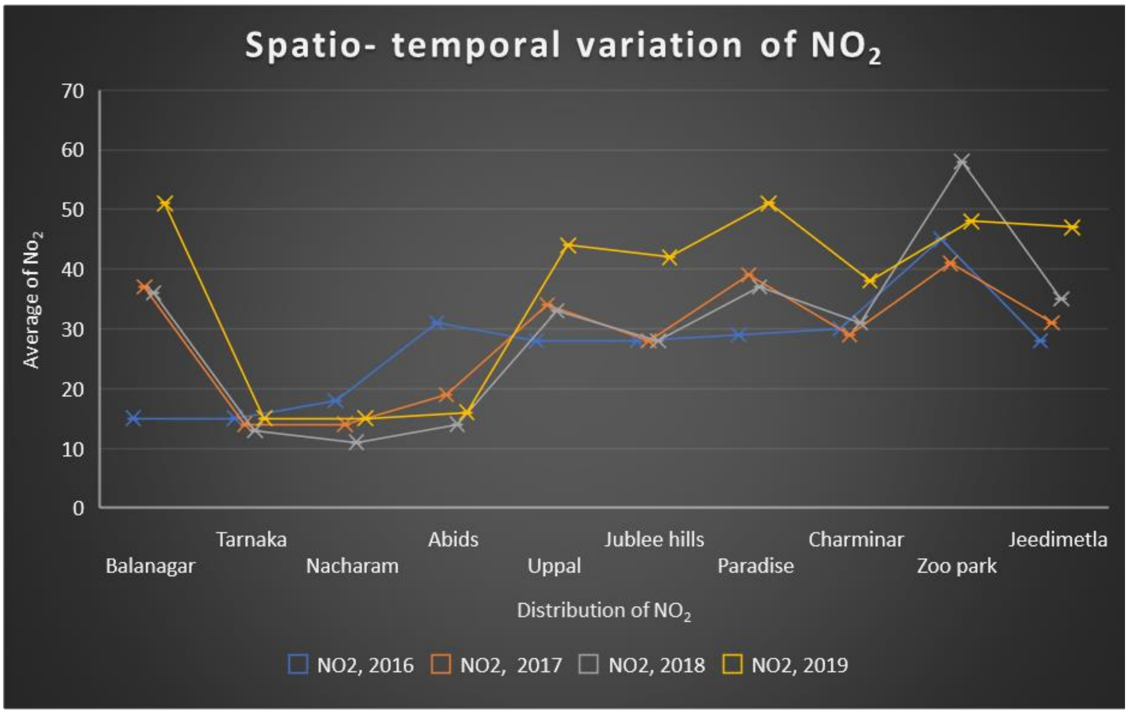
Table 3: Annual average (NO2) data in GHMC

Location	NO_2, 2016	NO_2, 2017	NO_2, 2018	NO_2, 2019
Balanagar	15	37	36	51

Tarnaka	15	14	13	15
Nacharam	18	14	11	15
Abids	31	19	14	16
Uppal	28	34	33	44
Jublee hills	28	28	28	42
Paradise	29	39	37	51
Charminar	30	29	31	38
Zoo park	45	41	58	48
Jeedimetla	28	31	35	47

Source: NAMP

Graph 3: shows the Spatio-temporal variation of NO2



5.3 Analysis: Ten Hyderabad sites' spatio-temporal fluctuation in Nitrogen Dioxide (NO2) levels across four years (2016–2019) is shown in this graph.

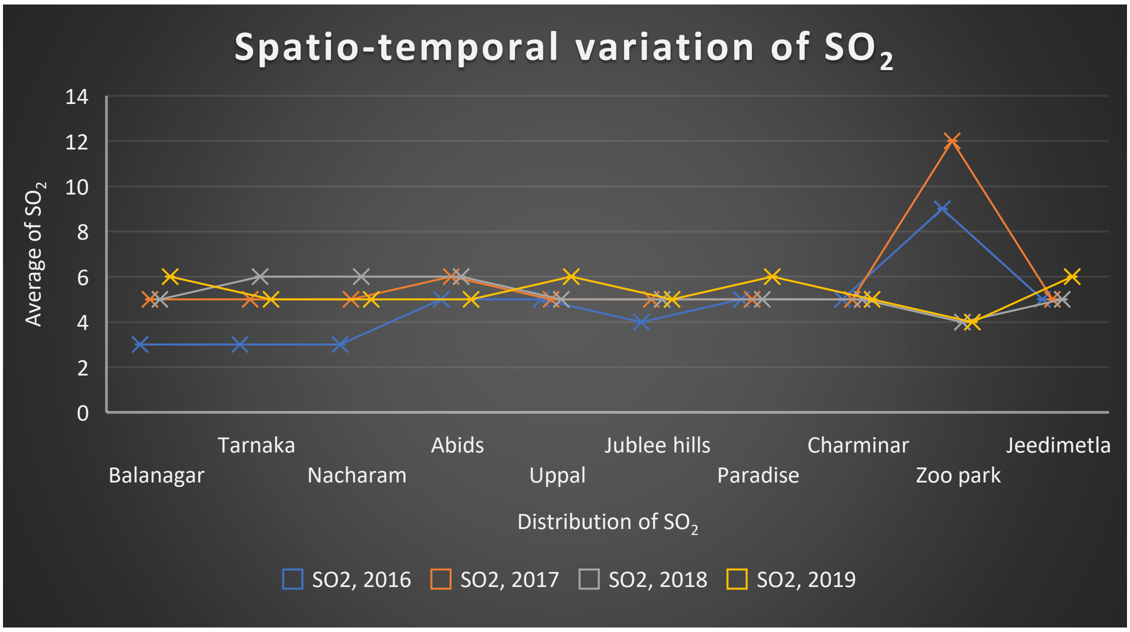
Spatial Variation: NO2 levels vary obviously amongst the several sites. Generally speaking, Tarnaka and Nacharam show the lowest NO2 levels across the period. at 2019 the NO2 levels at Jeedimetla and Zoo Park are highest. Balanagar exhibits a somewhat high NO2 level in 2016, which falls rather rapidly in the next years.

Time Trends: At Balanagar, NO2 levels are high in 2016; then, they decrease at the following few sites. Most of the sites show low levels as well. Though still somewhat low, NO2 levels in 2017 show a little rise at most sites. Although there is a very small rise at some sites, NO2 levels in 2018 are rather similar to 2017. At Zoo Park and Jeedimetla as well as Uppal and Paradise, NO2 levels climb dramatically in 2019.

Table 4: Annual average of SO_2 data in GHMC

Location	SO_2, 2016	SO_2, 2017	SO_2, 2018	SO_2, 2019
Balanagar	3	5	5	6
Tarnaka	3	5	6	5
Nacharam	3	5	6	5
Abids	5	6	6	5
Uppal	5	5	5	6
Jublee hills	4	5	5	5
Paradise	5	5	5	6
Charminar	5	5	5	5
Zoo park	9	12	4	4
Jeedimetla	5	5	5	6

Source: NAMP



Graph 4: shows the Spatio-temporal variation of SO_2

5.4 Analysis: This graph shows, over ten sites in Hyderabad over four years (2016–2019), the spatio-temporal variation of Sulphur Doxide (SO2) levels.

Generally speaking, SO2 levels are somewhat low at most places. Zoo Park shows a notable increase in SO2 levels in 2017 and 2019. Showing the next highest SO2 readings are Balanagar and Jeedimetla. Over the period, Tarnaka and Nacharam have the lowest SO2 levels.

Temporal variations: Most sites had somewhat steady 2016 SO2 values; Balanagar shows a small increase. Zoo Park shows a notable increase in SO2 levels in 2017; the Jeedimetla site shows a decline. In 2018 SO2 levels are low and quite constant everywhere. 2019 Zoo Park exhibits still another notable increase in SO2 levels.

The recurrent elevated SO2 values at Zoo Park in 2017 and 2019 strongly imply a localized source of SO2 emissions in that location. This calls more research to find the reasons.

6. Geostatistical Interpolation and Trend Analysis:

6..1 Geographical Information System (GIS) Application:

This work performed a thorough spatio-temporal analysis of the Air Quality Index (AQI) from 2016 to 2023 using a Geographical Information System (GIS) platform—more especially, ArcGIS 10.8. GIS offers a strong structure for viewing, analyzing, and interpreting geographical data, therefore allowing the study of AQI trends over both space and time.

6.2 Techniques for Geographic Analysis

Three interpolation techniques were applied within ArcGIS to produce spatially continuous representations of AQI from discrete monitoring station data:

Kriging interpolation is a geostatistical technique based on spatial autocorrelation of the data that forecasts values at unmeasured sites. It computes weights using known point spatial arrangement and distance as well as underlying spatial structure of the AQI data derived from a variogram. When data shows geographical reliance, this approach is especially helpful for producing accurate forecasts.

Spline interpolation generates aesthetically beautiful representation of the AQI distribution by fitting a smooth surface through the input points. By reducing surface curvature, this deterministic approach generates a flat surface exactly passing across the collected data points. Spline interpolation helps to create aesthetically pleasing maps and identify generally trending AQIs.

Estimates at unmeasured sites using IDW interpolation—which allocates weights to known sites based on their inverse distance from the projected location—are Higher weights for nearby points reflect their stronger effect on the expected value. Designed for quick estimates of AQI distribution, IDW is a simple, computationally effective method.

By applying these methods on the AQI data for every year between 2016 and 2023, annual AQI distribution maps were produced. By means of comparison between these maps, the spatio-temporal dynamics of AQI were explored over time, therefore exposing trends and patterns in changes in air quality over the study area. ArcGIS 10.8 offer the necessary tools for data management, spatial analysis, and map development to support an all-encompassing research of air pollution trends.

6.3 Analysis & Results:

4.1 Average Annual AQI, 2016, GHMC

Location	Lat	Long	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Average
Balanagar	17.4814	78.449	163	176	116	123	108	102	93	104	85	110	162	155	1497	12475.00
Uppal	17.3984	78.5583	112	102	94	92	86	91	73	67	66	104	127	144	1158	9650.00
Jubilee Hills	17.4326	78.4071	106	123	106	108	101	93	76	78	65	104	118	165	1243	10358.33
Paradise	17.4435	78.485	126	130	123	127	119	113	92	102	90	112	133	160	1427	11891.67
Charminar	17.3616	78.4747	123	119	105	110	98	98	83	84	71	101	145	170	1307	10891.67
Jeedimetla	17.5197	78.4586	151	123	122	114	107	92	75	76	73	112	159	155	1359	11325.00

Abids	17.393	78.473	123	112	111	115	90	77	84	76	68	98	123	126	1203	10025.00
Langarhouse	17.3782	78.4208	113	116	107	86	70	69	65	64	54	73	79	109	1005	8375.00
Madhapur	17.4486	78.3908	94	88	88	82	68	58	55	49	42	65	98	102	889	7408.33
MGBS	17.3799	78.486	79	80	95	93	71	66	68	54	47	73	81	88	895	7458.33
Chikkadapally	17.4009	78.4965	87	81	88	74	66	74	65	76	61	87	96	105	960	8000.00
Kukatpally	17.4875	78.3953	96	82	78	83	79	79	67	65	63	91	125	126	1034	8616.67
Nacharam	17.4308	78.5595	117	124	120	117	106	100	94	67	59	100	119	126	1249	10408.33
Rajendranagar	17.322	78.4023	63	75	67	71	65	64	71	60	57	66	75	75	809	6741.67
BPPA	17.4251	78.4878	77	76	70	52	66	53	42	47	39	57	79	103	761	6341.67
Panjagutta	17.4254	78.4505	115	104	113	105	109	105	106	107	-	-	-	-	864	10800.00
HCU	17.4614	78.3346	101	90	101	91	62	48	43	42	52	100	159	159	1048	8733.33
Zoo park	17.3506	78.4523	170	133	125	109	84	-	-	42	40	122	241	242	1308	13080.00
Sanathnagar	17.4563	78.4439	152	96	110	93	93	57	40	35	41	93	158	193	1161	9675.00
R C Puram	17.5192	78.3066	98	97	93	91	61	56	48	56	47	84	97	91	919	7658.33

Table 5: Source CPCB, NAMP, TSPCB

6.4 Spatial Analysis of 2016 Annual Air Quality:

Spatial analysis of Hyderabad's 2016 air quality, utilizing Inverse Distance Weighted (IDW), Spline, and Kriging interpolation, consistently revealed a heterogeneous distribution of pollutants across the city. Central and, in the case of Kriging, eastern Hyderabad exhibited significantly elevated levels of air pollution, categorized as "Poor," "Very Poor," and "Severe," indicating substantial pollutant concentrations likely due to high urban density and industrial activity. Conversely, peripheral regions consistently demonstrated comparatively improved air quality, falling within the "Good" to "Moderate" categories. These spatial variations, effectively visualized by each interpolation method, underscore the imperative for targeted interventions in Hyderabad's urban core to mitigate air pollution and enhance public health.

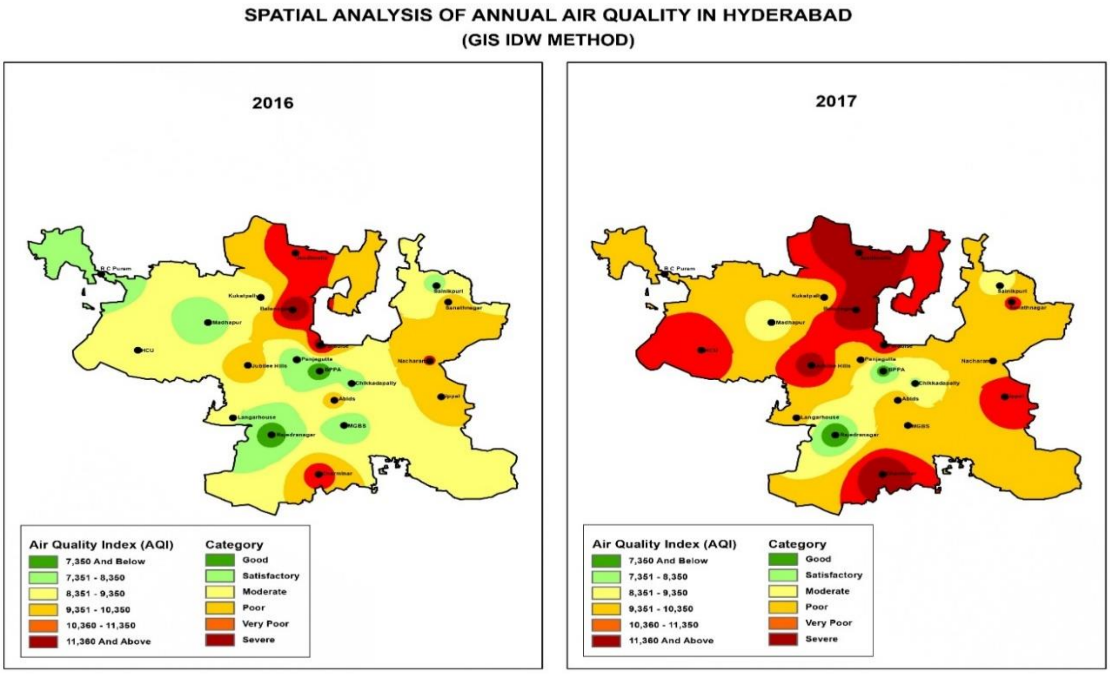


Fig 2 shows the Spatial analysis of AAQ in GHMC for 2016-2017 (GIS IDW METHOD)

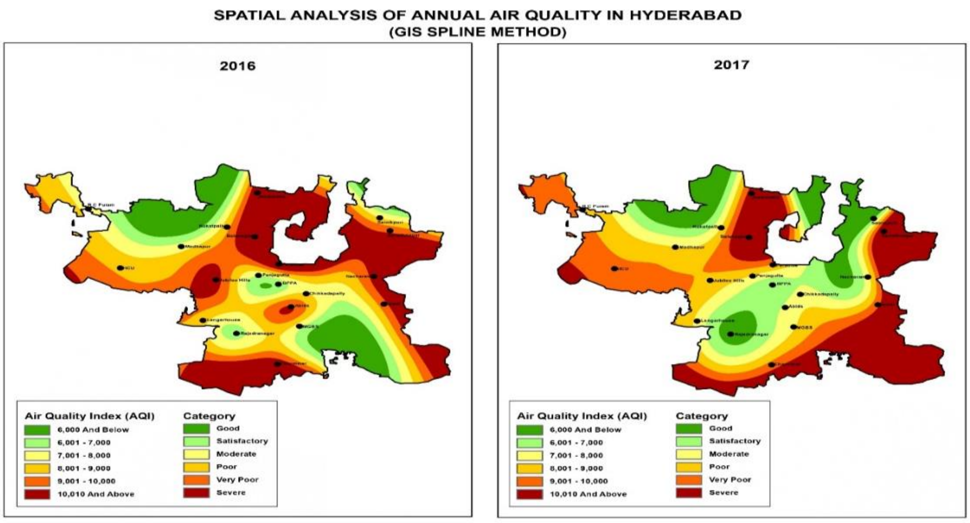


Fig 2 shows the Spatial analysis of AAQ in GHMC for 2016-2017 (GIS Spline METHOD)

Average Annual AQI, 2017, GHMC

Location	Latitude	Long	jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Average
Balanagar	17.4814	78.449	155	160	156	183	166	132	103	120	123	125	136	136	1695	14125.00
Uppal	17.3984	78.5583	147	147	130	159	103	72	75	73	85	96	125	135	1347	11225.00

Jubilee Hills	17.4326	78.4071	118	132	127	160	131	113	96	102	107	132	115	126	1495	12458.33
Paradise	17.4435	78.485	135	131	126	163	137	97	88	80	82	104	105	132	1380	11500.00
Charminar	17.3616	78.4747	123	157	142	199	171	84	82	100	114	120	135	138	1565	13041.67
Jeedimetla	17.5197	78.4586	172	163	155	180	149	88	94	90	112	130	127	142	1602	13350.00
Abids	17.393	78.473	145	131	120	113	80	74	84	62	79	91	91	119	1189	9908.33
Langarhouse	17.3782	78.4208	113	115	110	119	92	66	72	69	88	88	112	114	1158	9650.00
Madhapur	17.4486	78.3908	101	104	86	102	109	47	40	43	74	77	104	109	996	8300.00
MGBS	17.3799	78.486	115	120	111	119	105	46	58	80	109	102	81	99	1145	9541.67
Chikkadapally	17.4009	78.4965	106	102	95	104	90	51	61	59	72	83	76	85	984	8200.00
Kukatpally	17.4875	78.3953	119	109	117	129	94	66	76	70	82	88	130	149	1229	10241.67
Nacharam	17.4308	78.5595	116	118	104	118	126	76	60	52	77	109	106	108	1170	9750.00
Rajendranagar	17.322	78.4023	91	88	82	76	72	56	35	38	52	51	59	63	763	6358.33
BPPA	17.4251	78.4878	104	82	76	86	62	39	44	44	46	67	64	100	814	6783.33
HCU	17.4614	78.3346	133	128	108	132	94	45	47	52	65	97	96	142	1139	9491.67
Sanathnagar	17.4563	78.4439	175	166	115	118	82	43	36	46	58	128	123	237	1327	11058.33
Zoo park	17.3506	78.4523	179	203	136	167	128	76	56	63	83	121	128	223	1563	13025.00
R C Puram	17.5192	78.3066	90	94	88	89	81	61	49	43	48	68	80	97	888	7400.00

Table 6: Source CPCB, NAMP, TSPCB

6.5 Spatial Analysis of 2017 Annual Air Quality:

Using IDW, Spline, and Kriging, geographical analysis of Hyderabad's 2016 air quality exposed clear trends. While the "Good" to "Moderate" air quality of outer areas, IDW found central Hyderabad as a pollution hotspot with "Poor" to "Severe" AQI. Probably reflecting urban density and industrial activity, spline interpolation emphasized a gradient from "Good" air quality in the west to "Very Poor" conditions in central and northern parts. While surrounding areas showed improved air quality, Kriging precisely mapped particular high-AQI sites like Balanagar and Charminar as "Very Poor" to "Severe" hotspots, therefore verifying the method's efficacy in depicting pollution patterns and seasonal changes. All three approaches highlight how urgently Hyderabad's metropolitan core needs focused pollution reducing solutions.

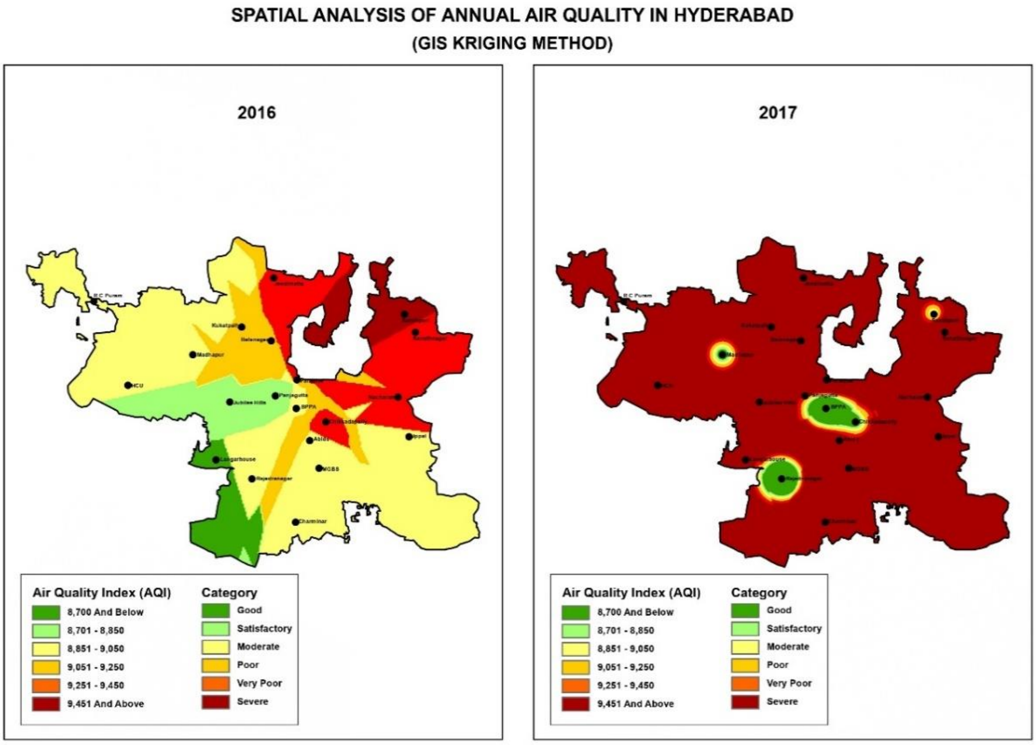


Fig 4 shows the Spatial analysis of AAQ in GHMC for 2016-2017 (GIS Kriging method)

Average Annual AQI, 2018, GHMC

Location	Lat	Long	Jan	Feb	March	April	May	June	July	Aug	Sep	Oct	Nov	Dec	Total	Average
Balanagar	17.4814	78.449	141	129	127	127	121	107	90	97	123	132	136	148	1478	12316.67
Uppal	17.3984	78.5583	141	126	126	112	107	87	85	82	91	107	122	134	1320	11000.00
Jubilee Hills	17.4326	78.4071	129	124	124	104	116	109	100	101	106	106	135	123	1377	11475.00
Paradise	17.4435	78.4851	130	125	117	106	118	104	83	93	102	96	102	106	1282	10683.33
Charminar	17.3616	78.4747	145	128	117	102	101	106	91	97	111	123	111	129	1361	11341.67
Jeedimetla	17.5197	78.4586	135	141	128	126	126	97	83	105	125	129	154	136	1485	12375.00
Abids	17.393	78.473	126	122	112	99	105	98	90	91	85	100	94	106	1228	10233.33

Langarhouse	17.3782	78.4208	116	128	113	90	97	89	75	84	103	103	100	98	1196	9966.67
Madhapur	17.4486	78.3908	112	100	105	104	97	72	71	68	84	99	91	105	1108	9233.33
MGBS	17.3799	78.486	102	107	110	89	83	73	75	86	98	100	100	105	1128	9400.00
Chikkadapally	17.4009	78.4965	99	99	96	99	90	81	76	82	94	95	88	108	1107	9225.00
Kukatpally	17.4875	78.3953	144	131	127	120	111	100	83	78	97	125	123	126	1365	11375.00
Nacharam	17.4308	78.5595	115	106	123	113	114	107	88	84	90	101	91	98	1230	10250.00
Rajendranagar	17.322	78.4023	61	56	60	55	60	48	46	64	72	86	73	93	774	6450.00
BPPA	17.4251	78.4878	88	78	86	62	74	67	53	60	75	77	74	90	884	7366.67
HCU	17.4614	78.3346	146	106	107	93	93	56	42	41	73	111	112	129	1109	9241.67
Sanathnagar	17.4563	78.4439	229	125	122	83	69	45	33	33	60	86	163	202	1250	10416.67
Zoo park	17.3506	78.4523	217	123	115	97	89	50	44	48	94	157	165	216	1415	11791.67
R C Puram	17.5192	78.3066	78	98	95	95	97	65	55	41	53	81	89	96	943	7858.33

Table 7: Source CPCB, NAMP, TSPCB

6.6 Spatial Analysis of 2018 Annual Air Quality:

The 2018 Hyderabad AQI spatial distribution, analyzed using IDW, Spline, and Kriging, revealed distinct patterns. IDW highlighted central and localized hotspots of "Poor" to "Severe" pollution, contrasting with the "Satisfactory" to "Moderate" air quality in peripheral areas, emphasizing the impact of urban development. Spline interpolation provided a smoother, more detailed visualization, capturing nuanced AQI variations and highlighting the influence of anthropogenic activities in central regions. Kriging, accounting for spatial autocorrelation, indicated a predominantly "Severe" AQI across Hyderabad, suggesting pervasive pollution throughout the city and underscoring the urgent need for comprehensive mitigation strategies.

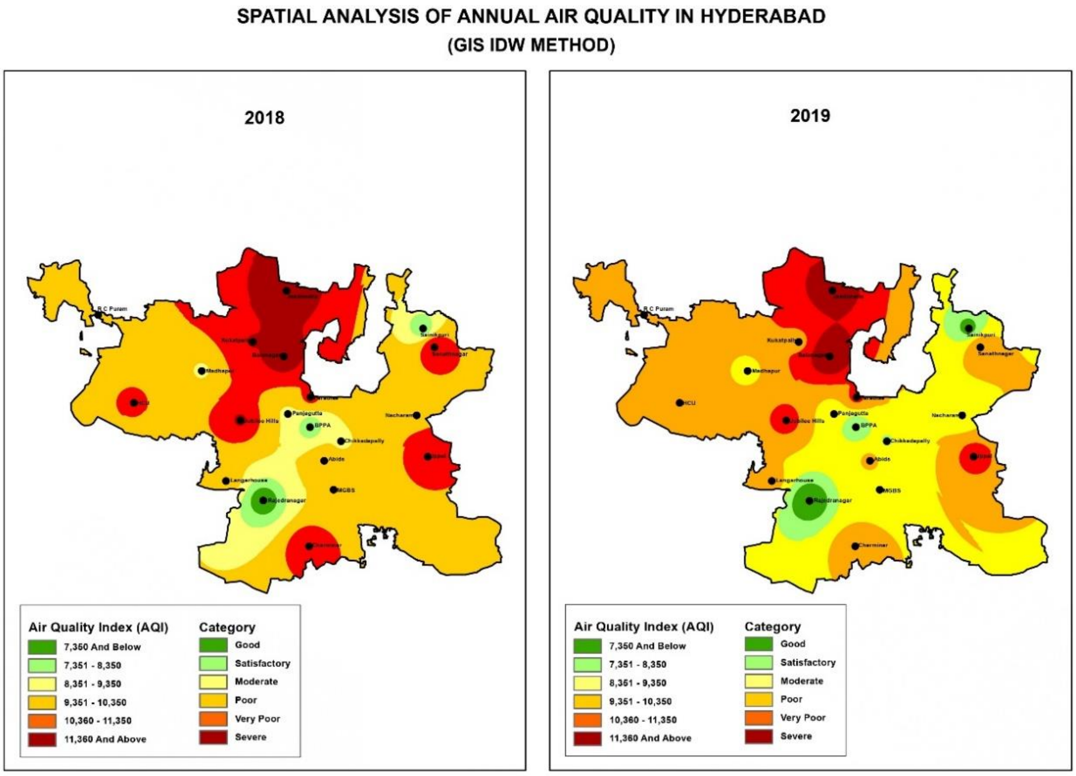


Fig 5 shows the Spatial analysis of AAQ in GHMC for 2018-2019 (GIS IDW method)

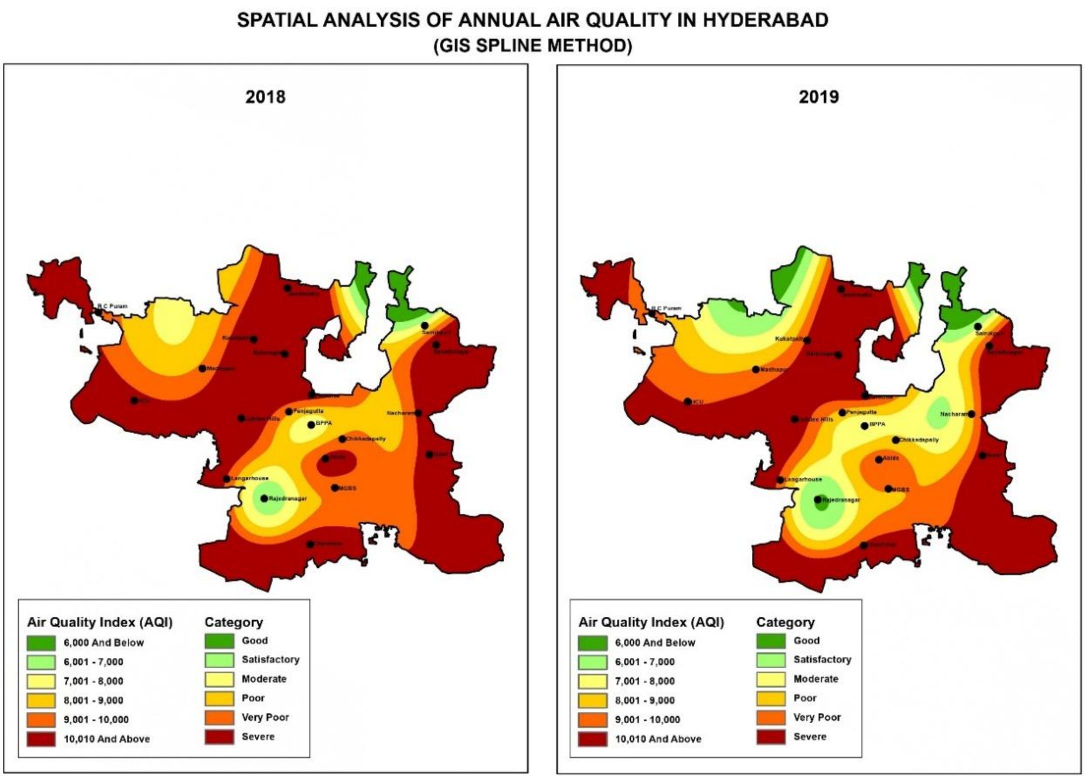


Fig 6 shows the Spatial analysis of AAQ in GHMC for 2018-2019 (GIS spline method)

Average Annual AQI, 2019, GHMC

Location	Lat	Long	Jan	Feb	March	April	May	June	July	Aug	Sep	Oct	Nov	Dec	Total	Average
Balanagar	17.4814	78.449	182	175	157	149	139	118	88	85	85	110	143	150	1581	13175.00
Uppal	17.3984	78.5583	139	124	126	92	108	84	83	77	78	102	142	144	1299	10825.00
Jubilee Hills	17.4326	78.4071	151	147	125	105	104	92	83	71	79	99	112	132	1300	10833.33
Paradise	17.4435	78.485	133	137	108	113	114	101	91	71	81	105	102	124	1280	10666.67
Charminar	17.3616	78.4747	137	136	110	100	109	83	75	66	72	95	108	131	1222	10183.33
Jeedimetla	17.5197	78.4586	161	162	153	121	120	105	91	83	87	103	123	146	1455	12125.00
Abids	17.393	78.473	115	98	105	95	108	100	88	74	88	80	103	98	1152	9600.00
Langar House	17.3782	78.4208	103	94	100	87	102	83	88	85	98	109	106	117	1172	9766.67
Madhapur	17.4486	78.3908	109	97	106	92	104	77	75	55	76	91	106	103	1091	9091.67
MGBS	17.3799	78.486	112	96	108	83	105	94	79	64	67	73	105	106	1092	9100.00
Chikkadapally	17.4009	78.4965	108	85	79	77	93	79	75	68	72	69	99	86	990	8250.00
Kukatpally	17.4875	78.3953	142	126	113	91	101	77	74	66	73	88	121	141	1213	10108.33
Nacharam	17.4308	78.5595	107	92	89	80	96	64	70	67	73	87	110	107	1042	8683.33
Rajendra nagar	17.322	78.4023	92	95	79	56	53	49	35	39	39	45	61	69	712	5933.33
BPPA	17.4251	78.4878	99	82	75	72	67	63	63	64	59	61	82	88	875	7291.67
HCU	17.4614	78.3346	145	112	106	91	116	61	36	43	40	61	126	109	1046	8716.67
Sanathnagar	17.4563	78.4439	211	111	89	69	77	52	40	38	51	93	188	176	1195	9958.33
Zoo park	17.3506	78.4523	234	146	119	107	140	65	40	44	52	89	203	190	1429	11908.33
R C Puram	**17.5192**	**78.3066**	97	84	88	91	88	75	77	74	54	79	91	97	996	8300.00

Table 8: Source CPCB, NAMP, TSPCB

6.7 Spatial Analysis of 2019 Annual Air Quality:

In 2019, spatial analysis of Hyderabad's AQI using IDW, Spline, and Kriging revealed notable shifts compared to 2018.With a worrying extension of "Moderate" to "Poor" air quality into periphery locations, IDW and Spline both revealed a continuous high AQI in center areas, implying increasing pollution dispersion. On the other hand, Kriging displayed a heterogeneous pattern, with center parts staying "Severe" while periphery areas—especially south and east—saw improvements in "Moderate" and "Poor" levels, maybe reflecting localized pollution management effectiveness. Overall, 2019 data points to a dynamic air quality scenario whereby center pollution persists and varies in outer places.

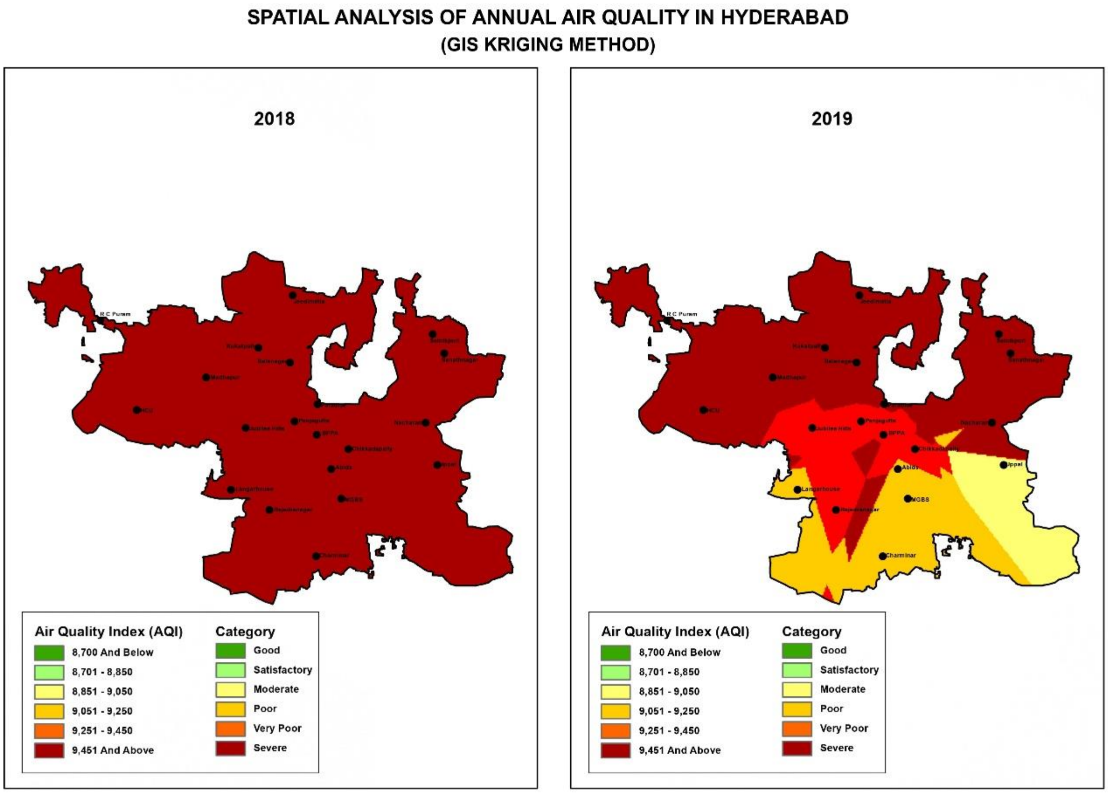


Fig 7 shows the Spatial analysis of AAQ in GHMC for 2018-2019 (GIS Kriging method)

Average Annual AQI, 2020, GHMC

Location	**Latitude**	**Longitude**	**Jan**	**Feb**	**March**	**April**	**May**	**June**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Total**	**Average**
Balanagar	17.4814	78.449	**126**	**119**	**136**	**80**	**86**	**67**	**74**	**94**	**88**	**98**	**135**	**157**	**1260**	**10500.00**
Uppal	17.3984	78.5583	**126**	**115**	**101**	**52**	**71**	**59**	**70**	**79**	**90**	**91**	**124**	**138**	**1116**	**9300.00**

Jubilee Hills	17.4326	78.4071	104	103	84	67	71	57	71	76	83	83	84	105	988	8233.33
Paradise	17.4435	78.4850	114	96	91	51	62	64	69	89	90	91	90	111	1018	8483.33
Charminar	17.3616	78.4747	125	117	110	81	65	60	68	76	75	99	96	119	1091	9091.67
Jeedimetla	17.5197	78.4586	148	129	117	78	95	68	69	86	86	102	121	145	1244	10366.67
Abids	17.393	78.473	90	97	102	57	63	54	51	49	49	60	94	103	869	7241.67
Langar House	17.3782	78.4208	95	96	96	55	61	49	47	75	59	68	82	99	882	7350.00
Madhapur	17.4486	78.3908	89	92	106	73	89	43	38	37	56	75	78	107	883	7358.33
MGBS	17.3799	78.486	92	86	99	-	-	-	-	-	63	65	69	96	570	8142.86
Chikkadapally	17.4009	78.4965	79	74	113	40	52	42	41	61	62	74	80	83	801	6675.00
Kukatpally	17.4875	78.3953	127	104	85	56	64	58	56	76	80	87	92	109	994	8283.33
Nacharam	17.4308	78.5595	121	91	97	-	50	48	50	60	59	69	97	97	839	7627.27
Rajendranagar	17.322	78.4023	51	47	52	36	44	31	28	41	39	61	61	73	564	4700.00
BPPA	17.4251	78.4878	101	77	82	41	46	37	33	55	51	61	75	94	753	6275.00
HCU	17.4614	78.3346	91	89	73	60	73	46	40	33	52	93	109	141	900	7500.00
Sanathnagar	17.4563	78.4439	104	95	66	56	63	34	30	25	37	103	126	192	931	7758.33
Zoo park	17.3506	78.4523	150	131	94	72	87	43	38	43	58	136	172	192	1216	10133.33

R C Puram	17.5192	78.3066	107	104	89	45	59	72	70	69	57	70	85	89	916	7633.33

Table 9: Source CPCB, NAMP, TSPCB

6.8 Spatial Analysis of 2020 Annual Air Quality:

Analysed with IDW, Spline, and Kriging, Hyderabad's AQI in 2020 produced different outcomes. With "Good" to "Moderate" AQI in southern and western locations, IDW and Spline revealed improved general air quality, most likely due to pandemic-related lockdowns; but, persisting "Poor" to "Very Poor" hotspots in central and northeastern areas. But kriging revealed a consistent "Good" AQI across the city, implying a persistent lack of notable air pollution. This difference draws attention to the several interpolation techniques and their sensitivity to localised changes against general trends.

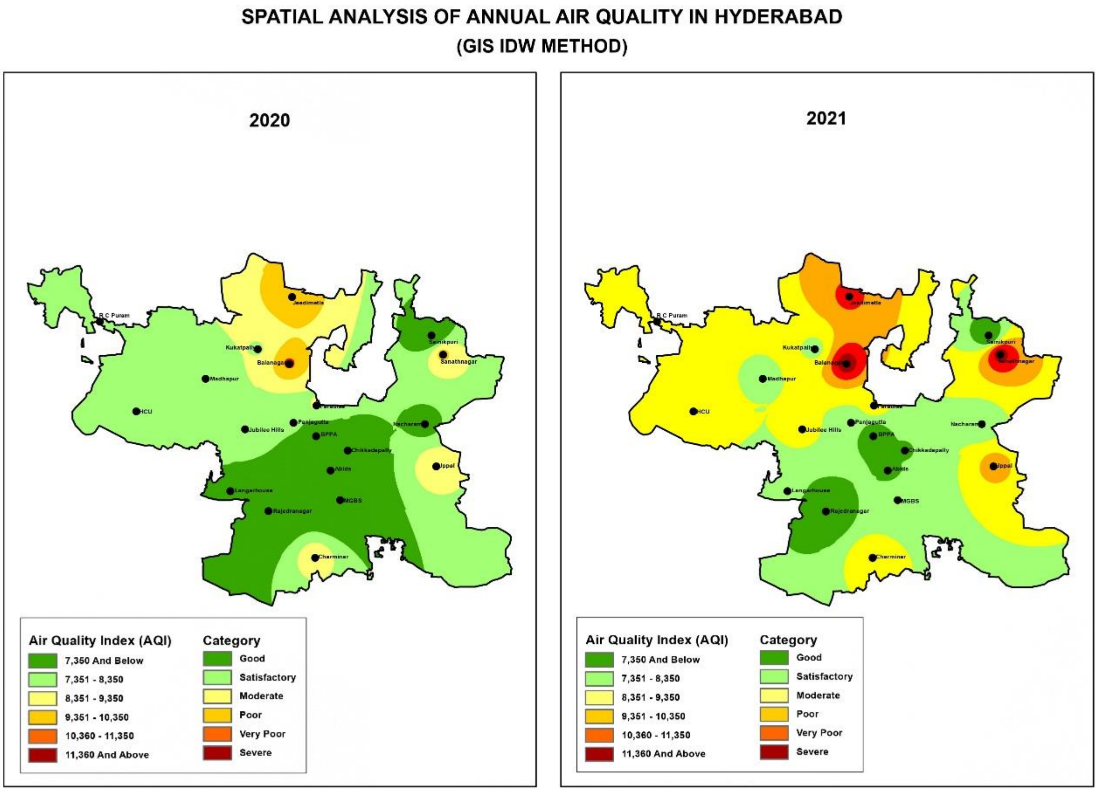


Fig 8 shows the Spatial analysis of AAQ in GHMC for 2020-2021 (GIS IDW method)

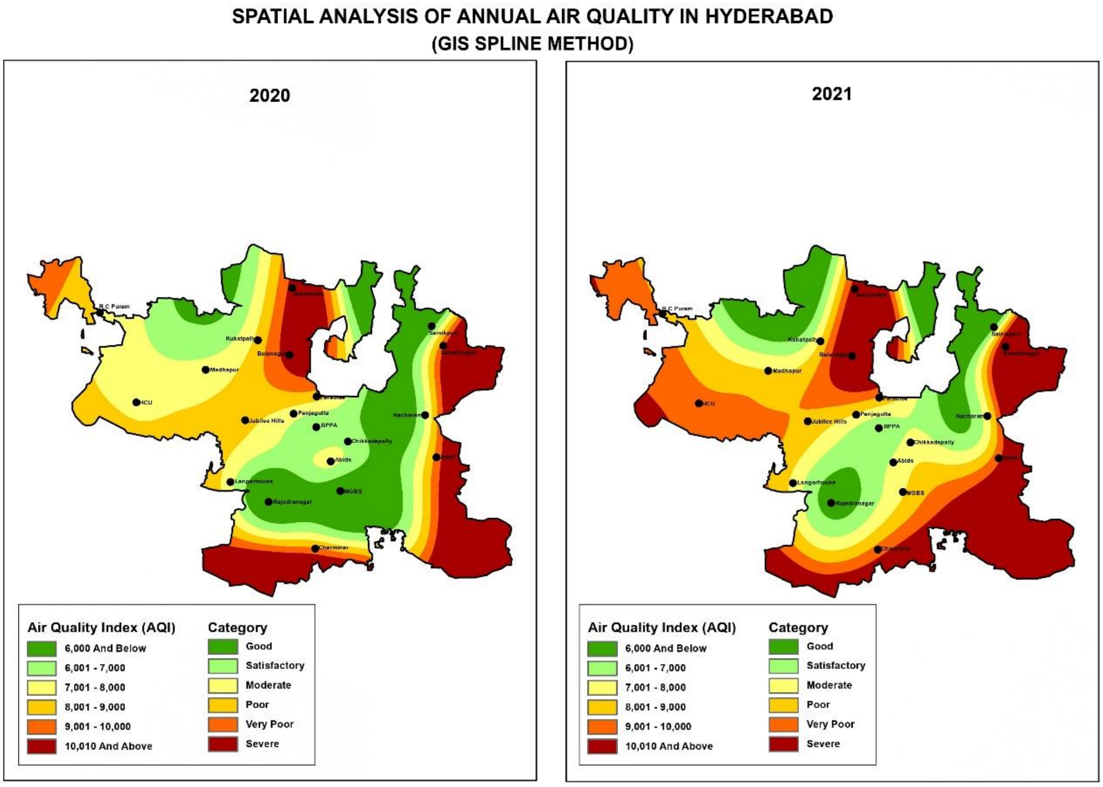


Fig 9 shows the Spatial analysis of AAQ in GHMC for 2020-2021 (GIS Spline method)

Average Annual AQI, 2021, GHMC

Location	Latitude	Longitude	Jan	Feb	March	April	May	June	July	Aug	Sep	Oct	Nov	Dec	Total	Average
Balanagar	17.4814	78.449	162	169	166	166	112	93	81	81	69	103	111	134	1447	12058.33
Uppal	17.3984	78.5583	138	134	136	128	64	69	75	70	55	94	91	116	1170	9750.00
Jubilee Hills	17.4326	78.4071	120	107	120	105	58	72	72	84	53	81	91	95	1058	8816.67
Paradise	17.44353	78.485096	126	115	116	100	64	61	74	66	69	84	90	113	1078	8983.33
Charminar	17.3616	78.4747	124	127	126	110	59	66	68	64	77	106	88	111	1126	9383.33

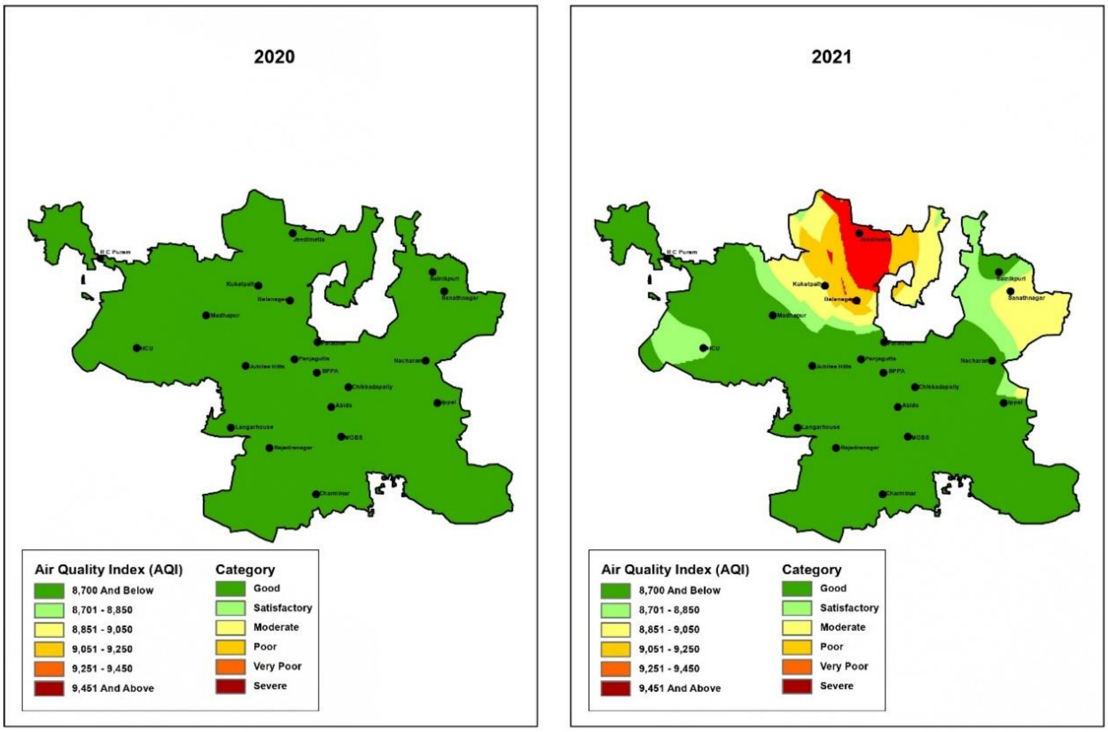
Jeedimetla	17.5197	78.4586	148	147	148	121	74	69	68	72	58	100	114	128	1247	10391.67
Abids	17.393	78.473	100	106	106	77	50	47	47	45	46	54	76	106	860	7166.67
KBRN Park	17.4198	78.4198	81	64	66	57	35	38	32	27	26	42	53	79	600	5000.00
Langar House	17.3782	78.4208	114	115	103	85	55	59	54	48	55	60	77	110	935	7791.67
Madhapur	17.4486	78.3908	123	114	111	97	60	55	48	47	42	67	89	108	961	8008.33
MGBS	17.3799	78.486	121	96	100	87	52	64	54	51	49	76	86	112	948	7900.00
Chikkadapally	17.4009	78.4965	102	95	93	93	50	63	50	50	49	59	70	99	873	7275.00
Kukatpally	17.4875	78.3953	113	109	100	92	50	53	53	55	51	85	102	98	961	8008.33
Nacharam	17.4308	78.5595	116	108	107	87	53	51	44	49	42	66	85	109	917	7641.67
Rajendranagar	17.322	78.4023	82	71	80	66	43	42	29	32	32	41	62	87	667	5558.33
BPPA	17.4251	78.4878	91	90	82	66	41	48	42	43	42	55	70	93	763	6358.33
HCU	17.4614	78.3346	117	113	114	104	57	43	31	35	36	86	89	128	953	7941.67
Sanathnagar	17.4563	78.4439	159	158	128	90	48	36	34	40	36	94	106	185	1114	9283.33
Zoo park	17.3506	78.4523	156	155	142	127	68	54	56	54	56	126	155	237	1386	11550.00
R C Puram	17.5192	78.3066	96	93	91	93	56	60	67	64	64	83	91	83	941	7841.67

Table 10: Source CPCB, NAMP, TSPCB

6.9 Spatial Analysis of 2021 Annual Air Quality:

In 2021, Hyderabad's AQI, analysed using IDW, Spline, and Kriging, showed a clear decline in air quality compared to 2020. IDW revealed a return of "Poor" to "Very Poor" AQI in central and north-eastern areas, with "Severe" hotspots reappearing, indicating a resurgence of pollution. Spline interpolation showed a similar trend, with central areas maintaining high AQI and an expansion of "Moderate" to "Poor" air quality into peripheral regions. Kriging also indicated localized "Poor" to "Severe" hotspots in central and north-eastern areas, contrasting with the uniform "Good" AQI in 2020. All methods highlight a significant deterioration in air quality in 2021, likely due to increased urban activity post-lockdowns, necessitating targeted pollution control.

SPATIAL ANALYSIS OF ANNUAL AIR QUALITY IN HYDERABAD
(GIS KRIGING METHOD)



Average Annual AQI, 2022, GHMC

Location	Latitude	Longitude	Jan	Feb	March	April	May	June	July	Aug	Sep	Oct	Nov	Dec	Total	Average
Balanagar	17.4814	78.449	139	141	137	111	116	103	81	53	89	81	104	113	1268	10566.67
Uppal	17.3984	78.5583	118	111	108	108	108	87	54	56	67	69	97	103	1086	9050.00
Jubilee Hills	17.4326	78.4071	98	101	97	85	91	79	64	54	58	81	86	95	989	8241.67

Paradise	17.4435	78.485	110	117	116	105	102	86	69	62	68	83	95	106	1119	9325.00
Charminar	17.3616	78.4747	110	99	107	89	94	92	77	67	73	93	104	114	1119	9325.00
Jeedimetla	17.5197	78.4586	128	144	136	118	110	90	63	81	76	77	104	113	1240	10333.33
Abids	17.393	78.473	103	97	114	99	96	85	50	63	68	64	89	100	1028	8566.67
Langar House	17.3782	78.4208	100	101	106	100	90	73	62	62	65	61	86	100	1006	8383.33
Madhapur	17.4486	78.3908	112	108	106	116	103	74	54	51	61	58	80	85	1008	8400.00
MGBS	17.3799	78.486	114	100	98	103	91	78	60	59	65	64	94	93	1019	8491.67
Chikkadapally	17.4009	78.4965	98	99	91	94	88	80	47	58	58	57	76	93	939	7825.00
Kukatpally	17.4875	78.3953	110	107	108	86	82	58	62	53	69	73	103	108	1019	8491.67
Nacharam	17.4308	78.5595	108	101	100	89	83	68	46	60	58	56	88	98	955	7958.33
Rajendranagar	17.322	78.4023	80	81	73	72	56	46	30	44	61	50	85	92	770	6416.67
BPPA	17.4251	78.4878	92	82	82	76	69	62	49	52	58	51	87	87	847	7058.33
HCU	17.4614	78.3346	128	112	116	100	101	69	52	52	52	82	129	110	1103	9191.67
Sanathnagar	17.4563	78.4439	141	107	123	81	74	47	41	38	50	97	178	155	1132	9433.33
Zoo park	17.3506	78.4523	192	158	177	119	111	61	41	42	55	134	273	236	1599	13325.00

R C Puram	**17.5192**	**78.3066**	**86**	**84**	**92**	**90**	**84**	**81**	**71**	**74**	**80**	**85**	**79**	**84**	990	8250.00

Table 11: Source CPCB, NAMP, TSPCB

6.10 Spatial Analysis of 2022 Annual Air Quality:

In 2022, spatial analysis of Hyderabad's AQI using IDW, Spline, and Kriging consistently revealed significant pollution hotspots in central areas, categorized as "Poor" to "Severe." IDW showed a varied distribution, with better air quality in southern and western peripheries. Spline highlighted a large "Severe" hotspot in central Hyderabad and "Poor" to "Very Poor" conditions in western and southwestern areas. Kriging similarly pinpointed a "Severe" central hotspot, with "Moderate" to "Poor" conditions in the west and southwest, and better air quality in the east. All three methods emphasize the spatial variability of pollution and the urgent need for targeted mitigation, particularly in central and western regions.

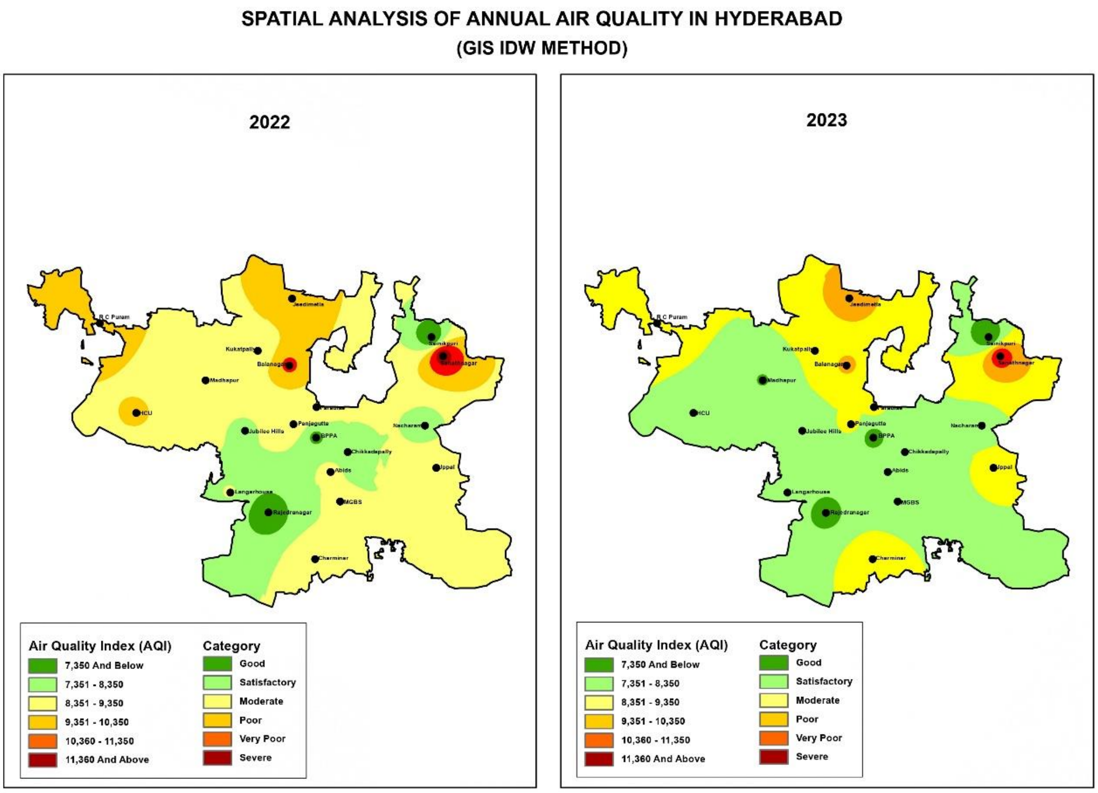


Fig 11 shows the Spatial analysis of AAQ in GHMC for 2022-2023 (GIS IDW method)

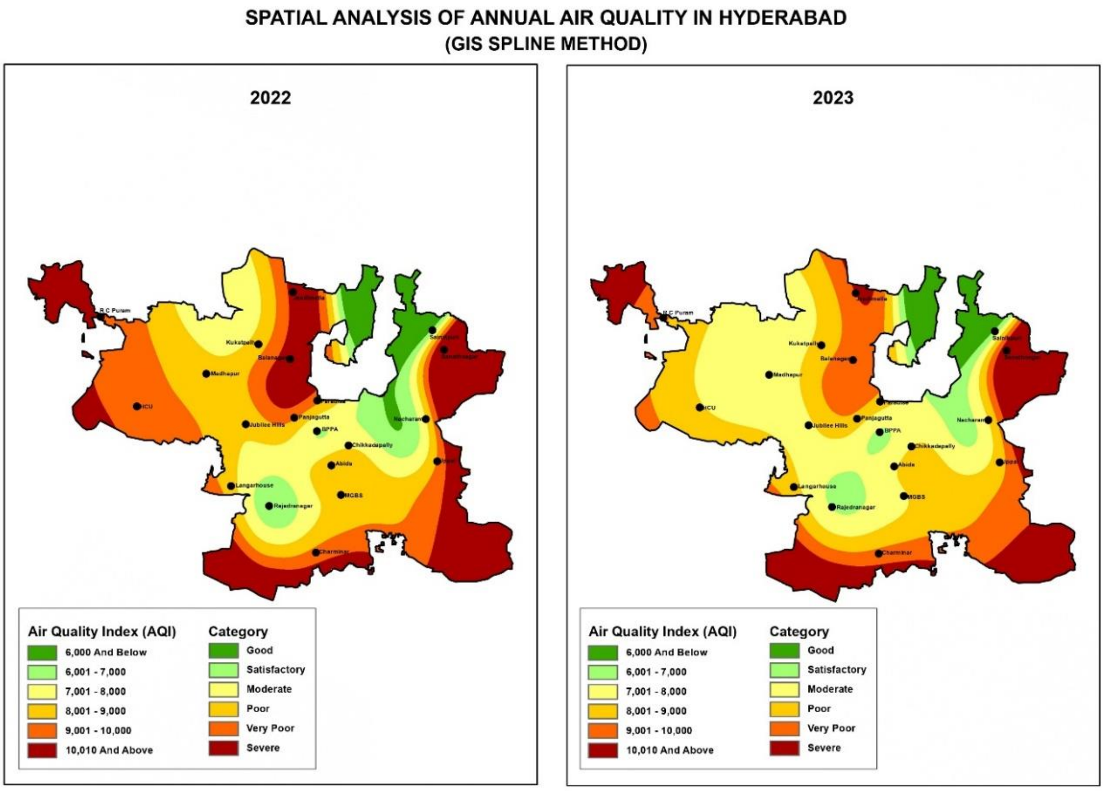


Fig 12 shows the Spatial analysis of AAQ in GHMC for 2022-2023 (GIS Spline method)

Average Annual AQI, 2023, GHMC

Location	**Latitude**	**Longitude**	**Jan**	**Feb**	**March**	**April**	**May**	**June**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Total**	**Average**
Balanagar	17.4814	78.449	117	128	115	101	101	103	61	78	75	87	93	88	1147	9558.33
Uppal	17.3984	78.5583	107	107	91	88	85	90	63	62	68	84	96	89	1030	8583.33
Jubilee Hills	17.4326	78.4071	95	92	85	86	79	73	60	66	62	77	88	82	945	7875.00
Paradise	17.4435	78.4850	109	115	104	83	91	84	57	58	69	86	89	85	1030	8583.33
Charminar	17.3616	78.4747	118	123	117	112	111	111	82	-	75	83	100	84	1116	10145.45

Jeedimetla	17.5197	78.4586	127	123	116	116	114	109	67	78	78	89	97	87	1201	10008.33
Abids	17.393	78.473	94	103	84	76	73	84	55	59	75	75	89	76	943	7858.33
Langar House	17.3782	78.4208	95	99	96	86	81	78	62	62	81	85	92	78	995	8291.67
Madhapur	17.4486	78.3908	94	105	96	84	80	75	54	56	56	81	95	-	876	7963.64
MGBS	17.3799	78.486	93	98	93	93	71	68	58	60	69	90	83	75	951	7925.00
Chikkadapally	17.4009	78.4965	92	95	90	89	75	78	55	62	79	74	88	79	956	7966.67
Kukatpally	17.4875	78.3953	113	111	91	90	85	88	48	55	64	90	88	80	1003	8358.33
Nacharam	17.4308	78.5595	97	94	90	86	75	72	65	70	71	75	89	78	962	8016.67
Rajendranagar	17.322	78.4023	84	94	83	75	65	63	56	47	57	67	80	63	834	6950.00
BPPA	17.4251	78.4878	89	95	74	72	66	55	59	41	53	57	92	76	829	6908.33
HCU	17.4614	78.3346	105	128	98	92	87	77	55	81	52	88	83	88	1034	8616.67
Sanathnagar	17.4563	78.4439	98	101	74	82	67	46	33	48	48	94	127	151	969	8075.00
Zoo park	17.3506	78.4523	214	219	156	130	124	61	36	71	55	120	130	127	1443	12025.00
ICRISAT	17.5178	78.279	131	155	107	89	82	62	44	58	50	95	111	114	1098	9150.00

Table 12: Source CPCB, NAMP, TSPCB

6.11 Spatial Analysis of 2023 Annual Air Quality:

In 2023, all three interpolation methods (IDW, Spline, and Kriging) indicated an improvement in Hyderabad's air quality compared to 2022. IDW showed a shift towards "Satisfactory" to "Moderate" AQI, with localized "Poor" to "Very Poor" hotspots remaining. Spline revealed a reduction in "Severe" pollution, moving towards "Satisfactory" to "Moderate" AQI, though "Moderate" pollution persisted in western areas. Kriging demonstrated the most significant improvement, with a shift towards "Good" to "Satisfactory" and "Moderate" AQI, showing a notable decrease in "Severe" pollution. All methods highlighted a positive trend, but emphasized the need for further analysis to understand the drivers of improvement and ensure sustained better air quality.

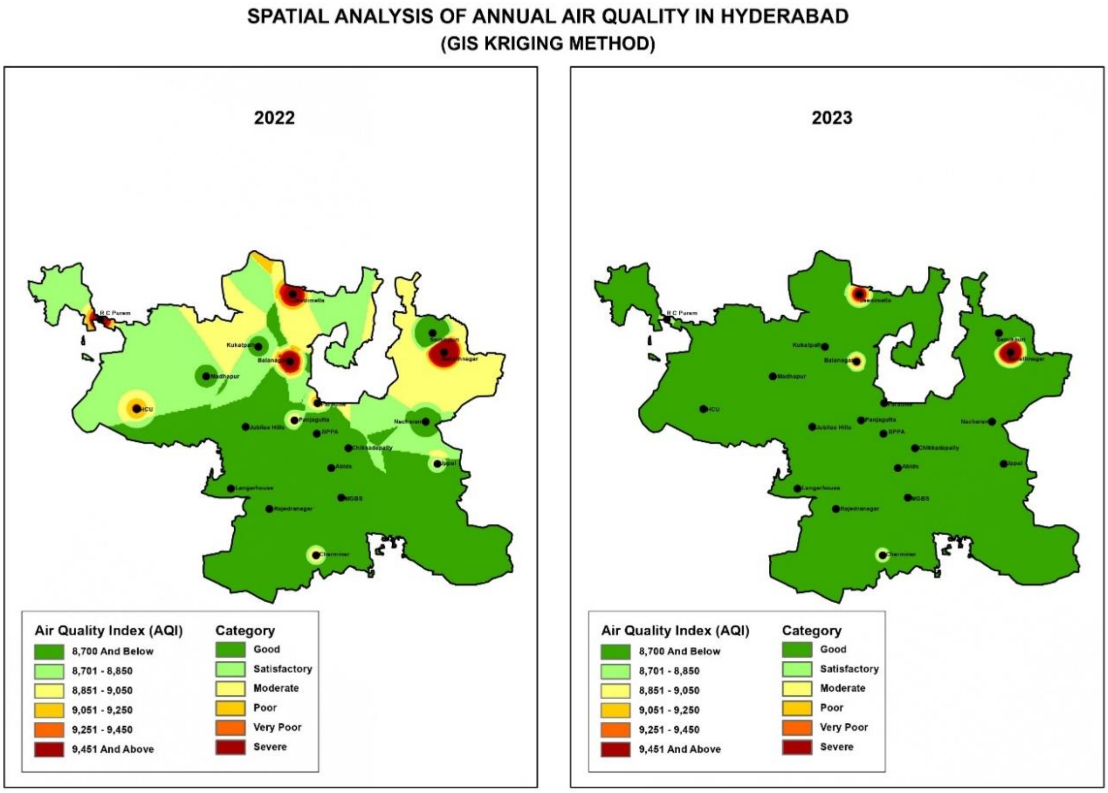


Fig 13 shows the Spatial analysis of AAQ in GHMC for 2022-2023 (GIS Kriging method)

7. Results

The spatio-temporal analysis of PM2.5, PM10, NO2, and SO2 levels across ten monitoring locations in Hyderabad from 2016 to 2019 revealed the following key findings:

Hyderabad's air quality data reveals significant spatial and temporal variations across pollutants. PM2.5 levels exhibited notable fluctuations, particularly in Balanagar and Uppal, with the Zoo Park consistently registering the highest concentrations, contributing to an overall concerningly high level citywide. PM10 was prevalent in industrial zones like Balanagar and Jeedimetla, with Abids experiencing a sharp spike in 2017, while Tarnaka and Nacharam maintained relatively low levels. NO2 concentrations were lowest in Tarnaka and Nacharam, but saw significant increases in the Zoo Park and Jeedimetla in 2019, contrasting with Balanagar's high levels in 2016 followed by a decline. SO2 levels were generally low, except for notable spikes at the Zoo Park in 2017 and 2019, and slightly elevated levels in industrial areas.

8. Discussion: Integrated Air Pollution Analysis and Mitigation in Hyderabad

This study, aiming to quantify air pollutant levels in Hyderabad's crucial commercial and industrial zones, revealed a complex pattern of spatio-temporal air quality dynamics, significantly impacting public health. The results, aligning with the broader geostatistical analysis of PM2.5, PM10, NO2, and SO2, demonstrate that air pollutant levels consistently exceed national ambient air quality standards, particularly in areas with high commercial and industrial activity, such as the city center and industrial estates. Temporal variations, with peak pollutant concentrations during rush hour, underscore the influence of traffic emissions.

The observed localized hotspots, notably at the Zoo Park, exhibiting elevated PM2.5, SO2, and a surge in NO2, necessitate targeted source apportionment studies. This is further supported by the persistent high PM10 and SO2 levels in industrial areas like Balanagar and Jeedimetla, highlighting the urgent need for stricter industrial emission controls. The variations in NO2 and the generally high PM10 and PM2.5 point strongly to vehicle traffic as a major source, aggravated by Hyderabad's fast industrialization and urbanization.

With increased PM2.5, PM10, and NO2 providing major respiratory and cardiovascular hazards, the public health consequences are rather large. Although SO2 levels are typically modest, the Zoo Park's increases cause a localized risk. These results support the need of evidence-based solutions like better pollution standards for businesses and cars, stronger waste management practices, encouragement of greener energy sources, and best traffic management tactics.

Effective air pollution control depends on the integrated approach, which takes citywide and localized elements into account. The temporal fluctuations noted, which point to episodic events, highlight even more the need of a thorough air quality monitoring system including more regular observations and meteorological data. Better trend tracking and hotspot identification made possible by this network will Moreover, strong public awareness initiatives are necessary to inform neighbours on air pollution and its consequences for their health. In order to reduce air pollution and protect public health in Hyderabad, constant and focused efforts under direction of thorough source apportionment studies and integrated monitoring are very essential.

9. Conclusion:

By means of spatio-temporal study of PM2.5, PM10, NO2, and SO2 in Hyderabad, the complicated air quality scenario marked by localized pollution hotspots and major contributions from industrial and transportation emissions is highlighted at last. Several suggestions are vital to handle these issues: doing thorough source apportionment studies, especially in the Zoo Park and industrial areas, to identify particular emission sources; implementing stricter emission controls for businesses and vehicles, particularly in high-pollution zones; improving public transportation and supporting cleaner alternatives to lower traffic emissions; establishing a comprehensive air quality monitoring network for trend tracking and hotspot identification; and so developing robust public awareness campaigns on air pollution and its health impacts. Moreover, better analysis depends on more frequent measurements and meteorological data integration, thereby strengthening data collecting. Although Hyderabad has made success in several areas of pollution control, constant and focused efforts are essential to reduce localised pollution hotspots and the effect of traffic and industrial emissions, therefore guaranteeing better air quality for its people.

Persistent Spatial Heterogeneity: The analysis of AQI data from 2016 to 2023 reveals a consistent spatial pattern of air pollution across Hyderabad. Central areas and industrial zones, including Balanagar, Jeedimetla, and Sanathnagar, persistently exhibit higher AQI values, indicating poor air quality, while peripheral regions generally experience better air quality. This spatial disparity underscores the localized impact of urban and industrial activities on air quality. This observed spatial heterogeneity aligns with findings from Roy and Chatterjee (2019), who demonstrated significant spatial disparities in urban activity across different zones of Hyderabad due to varying levels of industrialization and residential density.

Dominant Impact of Urban and Industrial Activities: High urban density and traffic congestion as well as industrial and commercial activity help to significantly contribute to increased pollution levels in particular places. Using IDW, Spline, and Kriging interpolation techniques, the concentration of pollution in central Hyderabad clearly points to a relationship between anthropogenic activity and declining air quality. Common observations in air quality studies are the connection between urban development, industrial activity, and more pollution levels. The paper quotes various sources to support this, including those showing that "vehicular emissions and localized industrial activity" cause central Hyderabad to show high pollution.

Clear seasonal changes in AQI values show a repeating trend of higher readings in the winter months. This seasonal trend is probably caused by meteorological elements like temperature inversions and lower dispersion of pollutants, which calls particular attention to winter pollution control. With most sites showing higher AQI values during the winter months of November, December, and January, most likely due to temperature inversions and decreased dispersion of pollutants, a common occurrence in metropolitan settings, a clear seasonal pattern developed (Sharma & Dikshit, 2016).

Independent of the geostatistical interpolation technique used—IDW, Spline, or Kriging—the spatial analysis regularly finds central Hyderabad as a major pollution hotspot. The studies underline the application of several geostatistical techniques (IDW, Spline, and Kriging) and observe the consistency in the detection of pollution hotspots. This methodological agreement enhances the validity of the results since several techniques agree on same outcomes.

Need for Targeted Interventions: The persistence of pollution hotspots and the identified impact of urban and industrial activities emphasize the urgent need for targeted interventions to mitigate air pollution and improve public health in specific areas of Hyderabad

Recommendations: Future studies should prioritize improved data quality, refined interpolation, detailed source apportionment, and higher temporal resolution, while also addressing environmental justice and integrating findings into urban planning for effective pollution mitigation.

10. Limitations:

1. The study's findings are dependent on the accuracy and completeness of pre-existing data, which may contain inherent errors or inconsistencies.
2. Interpolation techniques provide estimations, and their accuracy is influenced by the distribution and density of monitoring stations. Sparse monitoring areas may result in less reliable spatial representations of pollution levels.
3. Using monthly AQI data may obscure short-term pollution fluctuations caused by specific events or daily variations. This reduces the ability to find very short-term pollution causes.
4. The study focuses on a specific set of pollutants, potentially overlooking others that contribute to air quality degradation.
5. While mentioned, the study might lack a detailed examination of the underlying causes of seasonal pollution variations. A deeper analysis of seasonal trends would be beneficial.

References:

1. Alam, M. (2004). Hyderabad, 1800-1900 A.D.. Mittal Publications.
2. Baklanov, A., Korsholm, U., Mahura, A., Petersen, C., & Gross, A. (2008). ENVIROHIRLAM: On-line coupled modelling of urban meteorology and air pollution. Advances in Science and Research,

2(1), 41–46.
3. Boznar, M., Lesjak, M., & Mlakar, P. (1993). A neural network-based method for short term predictions of ambient SO2 concentrations in highly polluted industrial areas of complex terrain. Atmospheric Environment Part B Urban Atmosphere, 27(2), 221–230.
4. Charlot, S., Musy, M., & Tournoud, M. G. (2002). Geographic information system for environmental pollution studies. *Environmental Modelling & Software*, *17*(4), 303-311.
5. Chung, K. F., Zhang, J., & Zhong, N. (2011). Outdoor air pollution and respiratory health in Asia. Respirology, 16(7), 1023–1026.
6. Dünnebeil, G., Marjanović, M., & Žarko, I. P. (2017). Approaches to fuse fixed and mobile air quality sensors. May International symposium on environmental software systems (pp. 71–84).
7. Ghosh, S., & Guttikunda, S. K. (2020). Tracking air pollution and its impact on health in India. Environmental Research, 186, 109503.
8. Giustini, F., Ciotoli, G., Rinaldini, A., Ruggiero, L., & Voltaggio, M. (2019). Mapping the geogenic radon potential and radon risk by using Empirical Bayesian Kriging regression: A case study from a volcanic area of central Italy. The Science of the Total Environment, 661, 449–464.
9. Goovaerts, P. (1997). Geostatistics for natural resources evaluation. Oxford University Press.
10. Goovaerts, P. (2018). Geostatistical analysis methods for estimation of environmental pollution: A review. *International Journal of Environmental Research and Public Health*, 15(6), 1214. https://doi.org/10.3390/ijerph15061214
11. Gurjar, B. R., Jain, A., Sharma, A., Kumar, P., Nagpure, A. S., & Lelieveld, J. (2016). Urban pressures on climate and air quality. Atmospheric Environment, 128, 270-281.
12. Gurjar, B. R., Jain, A., Sharma, A., Kumar, P., Porwal, A., Bagchi, T., ... & Ojha, C. S. P. (2016). Human health risks in megacities due to air pollution. Atmospheric Environment, 142, 422-434.
13. Guttikunda, S. K., & Jawahar, P. (2014). Air pollution in Hyderabad, India: a review of the sources, impacts, and mitigation options. Air Quality, Atmosphere & Health, 7(4), 417-430.
14. Hurley, P. J., Physick, W. L., & Luhar, A. K. (2005). TAPM: A practical approach to prognostic meteorological and air pollution modelling. Environmental Modelling & Software, 20(6), 737–752.
15. Hyderabad sees marginal improvement in air quality, accessed March 14, 2025, https://www.newindianexpress.com/states/telangana/2024/Mar/22/hyderabad-sees-marginal-improvement-in-air-quality
16. IJERPH Special Issue. (n.d.). Geostatistics in environmental pollution. *International Journal of Environmental Research and Public Health*. Retrieved March 20, 2025, from https://www.mdpi.com/journal/ijerph/special_issues/geostatistics
17. Kumari, M., Basistha, A., Bakimchandra, O., & Singh, C. K. (2016). Comparison of spatial interpolation methods for mapping rainfall in Indian Himalayas of Uttarakhand region. Geostatistical and geospatial approaches for the characterization of natural resources in the environment. Cham: Springer159–168.
18. Lelièvre, N., Beaurepaire, P., Mattrand, C., & Gayton, N. (2018). AK-MCSi: A Krigingbased method to deal with small failure probabilities and time-consuming models. Structural Safety, 73, 1–11.
19. Mallet, V., & Sportisse, B. (2008). Air quality modeling: From deterministic to stochastic approaches. Computers & Mathematics with Applications, 55(10), 2329–2337.
20. Nagendra, H., Sudhira, H. S., & Tewari, R. (2004). Monitoring urban sprawl in the cities of Hyderabad and Bangalore, India using remote sensing. Remote Sensing for Environmental Monitoring, GIS

Applications, and Geology III, 5546, 321-332.
21. Palomino, I., & Martin, F. (1995). A simple method for spatial interpolation of the wind in complex terrain. Journal of Applied Meteorology, 34(7), 1678–1693.
22. Pope, C. A., & Dockery, D. W. (2006). Health effects of fine particulate air pollution: lines that connect. Journal of the Air & Waste Management Association, 56(6), 709-742.
23. Stone, B., Jr. (2008). Urban sprawl and air quality in large US metropolitan areas. Journal of environmental management, 86(4), 688-698
24. Tompson, A. B. (2001). Interpolation of environmental data. Journal of Spatial Hydrology, 1(2), 1-29.
25. United Nations, Department of Economic and Social Affairs, Population Division. (2018). World urbanization prospects: The 2018 revision. United Nations Publications.
26. Wong, F. T., Sulistio, A., & Syamsoeyadi, H. (2018). Kriging-based timoshenko beam elements with the discrete shear gap technique. International Journal of Computational Methods, 15(07), 1850064.
27. World Health Organization. (2021). Air pollution. Retrieved from https://www.who.int/news-room/fact-sheets/detail/air-pollution
28. World Health Organization. (n.d.). *Air pollution*, from https://www.who.int/health-topics/air-pollution
29. Xu, H., Bechle, M. J., Wang, M., Szpiro, A. A., Vedal, S., Bai, Y., ... Marshall, J. D. (2019). National PM2. 5 and NO2 exposure models for China based on land use regression, satellite measurements, and universal kriging. The Science of the Total Environment, 655, 423–433.