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Spatial Distribution Patterns of Urban Growth, Dasymetric Mapping, and Air Pollution Standard Index (ISPU) in Bogor Regency (2018-2023)

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ABSTRACT

Bogor Regency has undergone rapid industrialization and urban growth, raising concerns about deteriorating air quality and its health impacts. This study aims to analyze the spatial distribution of urban expansion and its relationship with air pollution levels between 2018 and 2023. Using Sentinel-5P and Sentinel-2A satellite imagery processed via Google Earth Engine (GEE), the research maps changes in land use and monitors key pollutants such as nitrogen dioxide (NO_2) and sulfur dioxide (SO_2). The Air Pollution Standard Index (ISPU) is used to classify air quality conditions. The results indicate a notable increase (16%) in urban areas, with population density rising from 178 to 180 inhabitants per hectare, and a shift toward higher pollution categories, with significant portions of the region now classified as "Unhealthy" increased from 17% in 2018 to 31% in 2023. The urban growth model demonstrated high accuracy (92.5%) and strong alignment with local monitoring data. Model evaluation showed a Mean Absolute Error (MAE) of 1.295 µg/m³ and Root Mean Square Error (RMSE) of 1.478 µg/m³, demonstrating strong agreement between predicted and observed data from the Bogor Regency Environmental Agency. These findings highlight the need for integrated urban planning and effective air quality management to reduce future health risks in Bogor Regency.

I. Introduction

Over the past two decades, Indonesia has experienced a dramatic deterioration in air quality[1]. From 1998 to 2016, the country shifted from being one of the cleanest nations globally to ranking among the twenty most polluted, with particulate matter concentrations increasing by 171 percent [2]. This rapid decline is largely attributed to technological advancement, expanding industrial activities, and the growing number of vehicles emitting harmful pollutants daily [3]. Bogor Regency exemplifies this trend, which is characterized by rapid industrial development and significant population growth, especially in Gunung Putri District. According to the Central Statistics Agency (BPS) of Bogor Regency [4], the population in Gunung Putri consistently increased from 301,852 in 2021 to 306,787 in 2023 [5]. Such growth exacerbates air pollution levels and poses serious public health risks [6]. The World Health Organization (WHO) and the United Nations Framework Convention on Climate Change (UNFCCC) reported that in 2010 [7], Indonesia suffered considerable health burdens linked to elevated carbon dioxide (CO_2) and particulate matter (PM10) concentrations [8]. These included 1,210,581 bronchial asthma cases, 173,487 bronchopneumonia cases, 2,449,986 acute respiratory infections, 336,273 pneumonia cases, 153,724 chronic obstructive pulmonary disease cases, and 1,246,130 coronary artery disease cases [9].

These significant health burdens highlight the urgent need for effective monitoring and mitigation strategies. Conventional ground-based air quality monitoring networks in Indonesia are still limited in coverage and cannot comprehensively capture spatial and temporal variations in pollutant levels, especially in rapidly developing areas like Bogor Regency. Therefore, integrating advanced geospatial technologies such as remote sensing has become crucial to provide timely, large-scale, and detailed information that supports evidence-based decision-making for air quality management.

Given these challenges, remote sensing offers an effective approach for air pollution monitoring by acquiring and analyzing Earth surface data through electromagnetic radiation captured by satellites. This method enables efficient geospatial analysis and temporal monitoring [10]. Google Earth Engine (GEE), a cloud-based platform, facilitates rapid and accurate processing of large-scale environmental data without requiring extensive local storage or preprocessing, thus enhancing the efficiency of environmental monitoring [11]. Previous studies have demonstrated the effectiveness of Sentinel-5 Precursor (Sentinel-5P) satellite imagery in identifying air pollution [12]. Launched by the European Space Agency (ESA), Sentinel-5P is equipped with the TROPOspheric Monitoring Instrument (TROPOMI) [13], which measures ultraviolet radiation at high spectral resolution with spatial resolution up to 7 km × 3.5 km at nadir [14]. Sentinel-5P data are instrumental in calculating the Air Pollution Standard Index (ISPU), which classifies air quality based on pollutant concentrations, enabling detailed and accurate monitoring [15]. The Air Pollution Standard Index (ISPU) is a dimensionless indicator representing ambient air quality based on its impact on human health and living organisms [16]. It incorporates key pollutants such as PM10, PM2.5, Carbon Monoxide (CO), Nitrogen Dioxide (NO_2), Sulfur Dioxide (SO_2), and Ozone (O_3). Clustering analysis of ISPU data facilitates identification of pollution patterns and classification into five categories: Good, Moderate, Unhealthy, Very Unhealthy, and Hazardous. Higher pollution levels correspond to increased environmental and health risks [17].

In light of these considerations, this study aims to analyze air pollution through the thesis entitled "Identification of Spatial Distribution Patterns of Urban Growth, Dasymetric Mapping, and Air Pollution Standard Index in Bogor Regency for the Years 2018 and 2023." The expected outcome is a spatial distribution map that supports more sustainable and efficient air pollution management.

II. METHODS

This research method employs a framework to plan and organize ideas based on objectives, consisting of three main components: problem identification, data collection, and data processing. Furthermore, the research activities implemented within this method are described as illustrated in Figure 1.

A. Problem Identification

The In the initial stage, a problem analysis is conducted to gather relevant information that aids in understanding the situation or issue at hand. This stage involves identifying the problem, its underlying causes, potential impacts, and the interrelationships involved, which collectively contribute to formulating effective solutions. Based on the problem analysis, it is evident that air pollution in Bogor Regency has increased, adversely affecting public health. This rise in pollution is primarily attributed to emissions from motor vehicle exhaust, which significantly influence air quality levels.

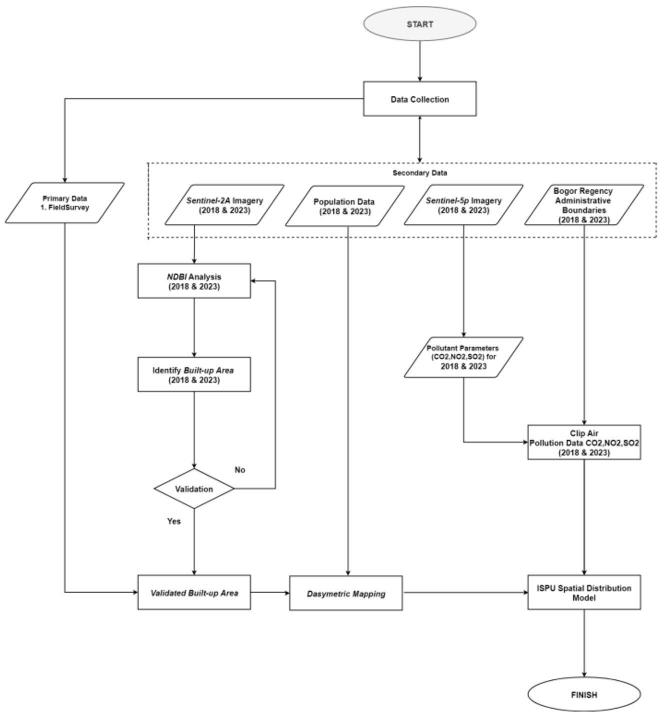

Figure 1 Thinking Framework

B. Data collection

The data used in this study include Sentinel-5P satellite imagery and Sentinel-2A satellite imagery obtained from the Google Earth Engine (GEE) database, spatial data of Bogor Regency from the Indonesian Topographic Map (Rupa Bumi Indonesia, RBI) in SHP format acquired from the Geospatial Information Agency's Geoportal https://tanahair.indonesia.go.id/portal-web and air polution data from the Bogor Regency Environmental Agency in the form of tables covering the periods of 2018 and 2023. Additionally, field surveys were conducted to support the data collection process.

C. Data Processing

In the data processing and analysis stage, the data utilized include Sentinel-2A imagery from 2018 and 2023, administrative boundaries of Bogor Regency, and field survey data.

1. Analysis of built up area

The built-up areas was conducted using the Normalized Difference Built-up Index (NDBI) method, as formulated in Equation (1).

$$NDBI = \frac{(SWIR-NIR)}{(SWIR+NIR)} \text{.................. (1)}$$

Where SWIR is the reflectance value from the Short-Wave Infrared band and NIR is the reflectance value from the Near-Infrared band. Higher NDBI values indicate a greater concentration of built-up or urbanized areas, while lower values represent less built-up regions. This index is dimensionless and does not require additional unit conversions, which simplifies its interpretation for identifying urban growth.

In this data processing stage, the classification of the Built-up Area index was performed using Sentinel-2A imagery obtained from Google Earth Engine. The data were classified into two categories: (1) Built-up and (2) Non Built-up. These two classes were derived from the NDBI calculation results. The threshold values for class separation were determined based on standard NDBI value ranges, ensuring accurate delineation of urban areas. The data processing steps in Google Earth Engine for identifying and analyzing built-up area expansion and its relationship with pollution patterns utilized Sentinel-2A imagery from 2018 and 2023, along with the administrative boundaries of Bogor Regency, as illustrated in Figure 2.

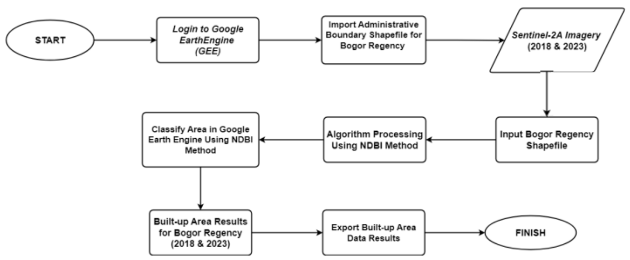

Figure 2 Detailed Workflow for Built-Up Area Classification Using Sentinel-2A and Google Earth Engine

2. Analysis of Air Pollution

In this stage, the classification of air pollution indices from Sentinel-5P imagery obtained via Google Earth Engine (GEE) was conducted based on the Air Pollution Standard Index (ISPU). The ISPU categorizes air quality into five classes: (1) Good, (2) Moderate, (3) Unhealthy, (4) Very Unhealthy, and (5) Hazardous. To align the ISPU scale with Sentinel-5P data, the unit conversion from mol/m³ (Sentinel-5P's original unit) to micrograms per cubic meter (µg/m³) is performed. Concentration data of SO_2, NO_2, and CO were extracted from GEE, processed, and standardized to international units (µg/m³). Pollutants such as NO_2, CO, and SO_2 predominantly disperse within the troposphere, at altitudes below 10 km (H), with their concentrations (C) assumed uniform across this height for simplification. Therefore, the original mol/m² units must be converted to µg/m³ to enable comparison with the national air quality threshold standards. Therefore, the concentration of pollutant substances in (mg/m³) is calculated as formulated in the equation 2.

$$C = \frac{C_{col}}{H} \cdot M \cdot A \text{ .... (2)}$$

Note:
C = Concentration of the substance in a specific unit (µg/m³).
Ccol = Column concentration (mol/m²).
H = Height or depth of the air column (m).
M = Molar mass of the substance (g/mol for substances such as SO_2, CO_2, NO).
MNO_2 = 46 g/mol (periodic table).
MSO_2 = 64 g/mol (periodic table).
MCO = 28 g/mol (periodic table).
A = Area.

The converted Sentinel-5P data from units of mol/m² to µg/m³ were then adjusted according to the ISPU classification criteria, as shown in Table 1.

Table 1 Adjustment of ISPU Scale Values with Sentinel-5P Data

Range and Classification		ISPU Parameter Value (µg/m³)		
ISPU Range	ISPU Category	*NO_2*	*CO*	*SO_2*
0-50	Good	80	4000	52
51-100	Moderate	200	8000	180
101-200	Unhealthy	1130	15000	400
201-300	Very Unhealthy	2260	30000	800
>300	Hazardous	3000	45000	1200

Source : PERMEN ISPU NO.14/MENLHK/SETJEN/KUM.1/7/2020 TENTANG ISPU

Next, the data processing and analysis stages were conducted using the Google Earth Engine platform, which involved processing Sentinel-5P imagery from 2018 and 2023. This stage encompasses the process of searching for and collecting data relevant to the study. Data processing is performed to facilitate the analysis of the relationship between air pollution and public health impacts. The data types are divided into two categories: spatial and non-spatial data. Spatial data consist of satellite imagery obtained through the Google Earth Engine platform, while non-spatial data were acquired from the Bogor Regency Environmental Agency. The non-spatial data include air pollution levels for the years 2018 and 2023, which were further verified through direct field surveys to validate the accuracy of the satellite-derived air pollution indicators. This workflow is illustrated in Figure 3, which outlines the integrated processing steps.

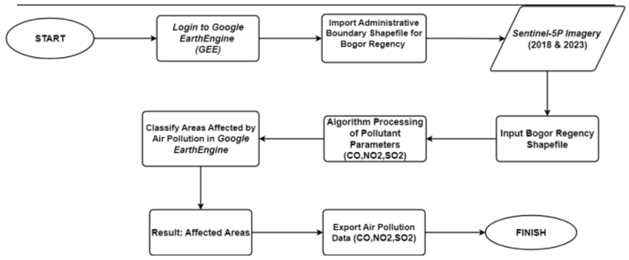

Figure 3 Integrated Workflow for Sentinel-5P Data Processing, Air Pollution Index Calculation, and Validation with Field Survey Data (2018 and 2023)

The following describes the processing and analysis of spatial data using ArcGIS Pro for the years 2018 and 2023 to obtain the number of affected population. This step includes overlaying air pollution data with population density maps to estimate exposure levels and potential health impacts. This process is illustrated in Figure 4.

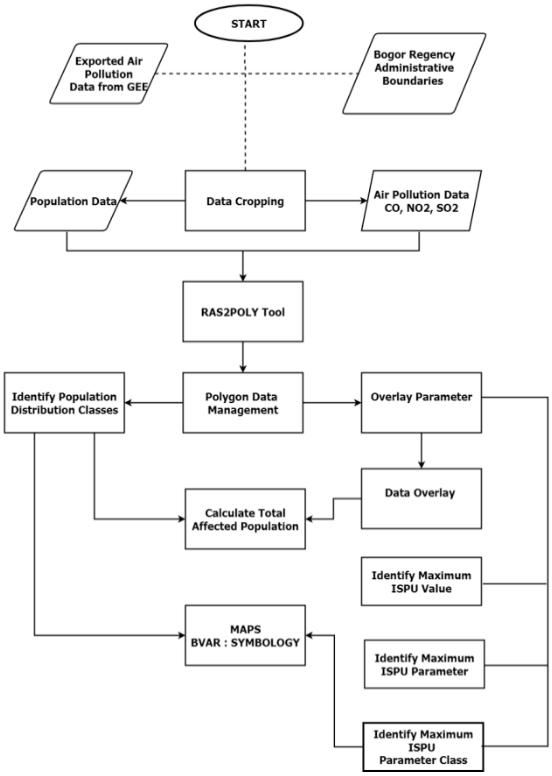

Figure 4 Spatial Overlay and Population Exposure Analysis Using ArcGIS Pro for Air Pollution Impact Assessment (2018 and 2023)

III. RESULTS

This chapter presents the research findings that have been analyzed, including the analysis and identification of urban growth, dasymetric mapping, and air pollution. It also covers the modeling of the spatial distribution patterns of ISPU air pollution in Bogor Regency for the years 2018 and 2023, as well as the integration of the spatial distribution model with both point and non-point pollution sources

A. Result Analysis Urban Growth

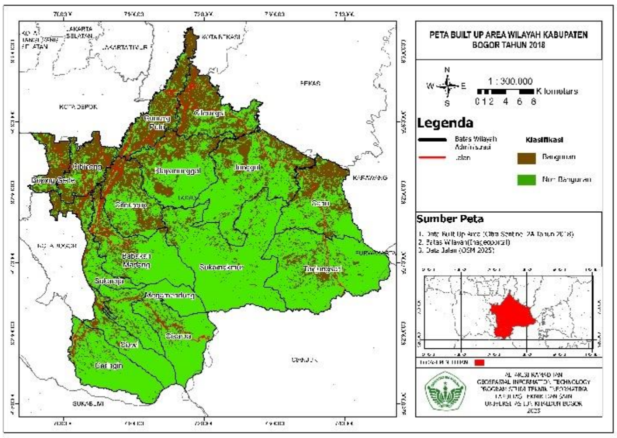

Figure 5 Built-up Area Map of Bogor Regency in 2018

The analysis of the built-up area extent in Bogor Regency for the year 2018 can be seen in Table 2.

Table 2 Analysis Results of Built-up Area Extent in Bogor Regency in 2018

No.	Wilayah Kabupaten Bogor	Nama Kecamatan	Luas Kecamatan (Ha)	Luas *Built up Area* Terbangun (Ha)	Persentase Luas *Built up Area* Terbangun (%)	*Luas Built up Area* Non Bangunan (Ha)	Persentase Luas *Built up Area* Non bangunan (%)
1.	Tengah	Babakan Madang	9.161,78	2.283,53	25	6.878,25	75
2.		Bojong Gede	2.732,69	1.948,68	71	784,01	29
3.		Caringin	7.775,45	817,04	11	6.958,41	89
4.		Ciawi	4.705,32	763,98	16	3.939,14	84
5.		Cibinong	4.660,28	3.204,64	69	1.452,97	31
6,		Cisarua	7.104,83	874,20	12	6.225,42	88
7.		Megamendung	6.344,38	742,07	12	5.602,43	88
8.	Timur	Cariu	8.475,24	3.337,00	39	5.138,24	61
9.		Cileungsi	7.009,29	4.383,35	63	2.616,51	37
10.		Citereup	6.933,26	3.588,38	52	3.345,01	48
11.		Gunung Putri	6.083,63	4.393,30	72	1.667,51	28
12.		Jonggol	13.536,63	4.168,64	31	9.367,56	69
13.		Klapanunggal	9.589,35	3.369,17	35	6.220,30	65
14.		Sukamakmur	18.204,53	1.488,39	8	16.712,48	92
15.		Sukaraja	4.382,28	1.643,30	38	2.731,97	62
16.		Tanjungsari	14.729,30	2.122,39	14	12.599,80	86
Luas total *Area* di Kabupaten Bogor Bagian Timur (Ha)			131.368 Ha	39.128 Ha atau 29,79%	-	92.240 Ha atau 70,21%	-
			100%				

Based on Table 2 above, the total area of Bogor Regency in 2018 was 131,368.03 hectares. The analysis results indicate that the largest built-up area in Bogor Regency was found in Gunung Putri District, with a total built-up area of

4,393.30 hectares, accounting for approximately 72% of the total area of Gunung Putri District.

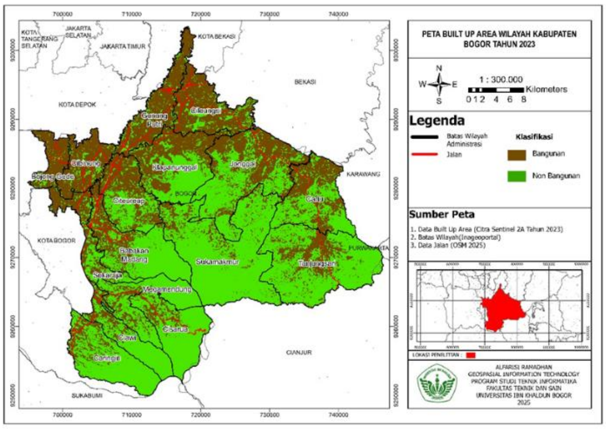

Figure 6 Built-up Area Map of Bogor Regency in 2023

The analysis of the built-up area extent in Bogor Regency for the year 2023 can be seen in Table 3

Table 3 Analysis Results of Built-up Area Extent in Bogor Regency in 2018

No.	Wilayah Kabupaten Bogor	Nama Kecamatan	Luas Kecamatan (Ha)	Luas *Built up Area* Terbangun (Ha)	Persentase Luas *Built up Area* Terbangun (%)	Luas *Built up Area* Non Terbangun (Ha)	Persentase Luas *Built up Area* Non Terbangun (%)
1.	Tengah	Babakan Madang	9.161,78	2.880,17	31	6.281,73	69
2.		Bojong Gede	2.732,69	2.422,7	89	310,62	11
3.		Caringin	7.775,45	1.400,55	18	6.375,30	82
4.		Ciawi	4.705,32	1.086,24	23	3.616,89	77
5.		Cibinong	4.660,28	3.979,91	85	677,70	15
6.		Cisarua	7.104,83	1.051,85	15	6.046,69	85
7.		Megamendung	6.344,38	1.229,12	19	5.115,38	81
8.	Timur	Cariu	8.475,24	4.009,39	47	4.465,85	53
9.		Cileungsi	7.009,29	5.616,26	80	1.383,61	20
10.		Citereup	6.933,26	4.004,03	58	2.929,36	42
11.		Gunung Putri	6.083,63	5.113,65	84	947,17	16
12.		Jonggol	13.536,63	6.320,79	47	7.215,41	53
13.		Klapanunggal	9.589,35	4.871,79	51	4.717,68	49
14.		Sukamakmur	18.204,53	2.077,50	11	16.123,38	89
15.		Sukaraja	4.382,28	2.546,69	58	1.828,58	42
16.		Tanjungsari	14.729,30	3.412,33	23	11.309,70	77
Luas Total Area Kabupaten Bogor (Ha)			131.368	52.023 atau 39,60 %	-	79.345 atau 60.40%	-

Based on Table 3 above, the total built-up area in Bogor Regency in 2018 was 131,368.03 hectares. The analysis shows that the largest built-up area in Bogor Regency in 2018 was located in Gunung Putri District, with a total built-up area of 4,392.82 hectares, accounting for 72% of the total area of Gunung Putri District. Meanwhile, according to Table 3, the total built-up area in Gunung Putri District increased by 16% in 2023 compared to 2018, reaching 5,113.59 hectares, which is approximately 84% of the total area of Gunung Putri District in 2023. The extent of built-up areas in each district of Bogor Regency is detailed accordingly.

Based on the graph illustrating the increase in built-up areas in Bogor Regency between 2018 and 2023, all districts experienced growth. Specifically, Tanjung Sari, Sukaraja, Sukamakmur, and Megamendung districts exhibited built-up area percentages of approximately 40%. Meanwhile, districts such as Caringin, Bojong Gede, and Babakan Madang showed slightly higher percentages, approaching 50%. However, by 2023, all districts demonstrated a significant surge in built-up area percentages, with the orange bars on the graph nearly reaching 100%. This indicates that within a five-year period, there has been a rapid expansion of built-up areas across all districts in Bogor Regency. as illustrated in Figure 7

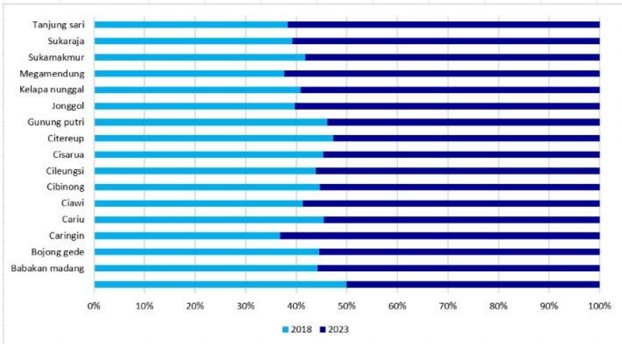

Figure 7 Comparison Graph of Built-up Area Increase in Bogor Regency for 2018 and 2023

B. *Result Analysis Dasymetric Mapping*

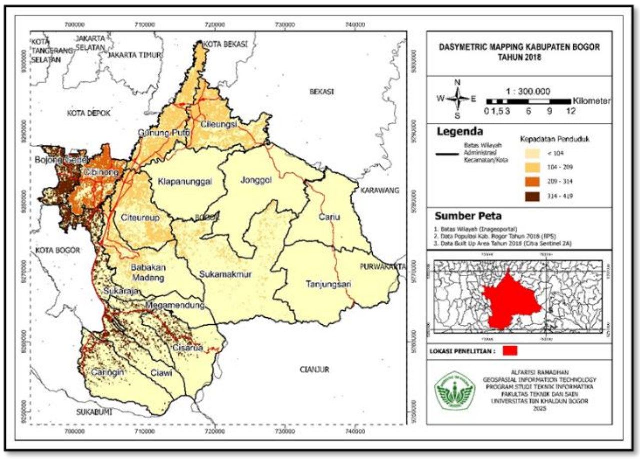

Figure 8 Layout Dasymetric Mapping of Bogor Regency in 2018

The population density values, expressed in persons per hectare (persons/ha), calculated in ArcGIS using the Calculate Geometry tool, can be seen in Table 4

Table 4 Population Density Values by District in Bogor Regency in 2018

No	Bogor Regency Area	Sub-District Name	Population Density (Persons/Ha)	Population Density Classification
1	Central	Babakan Madang	127	Low
2		Bojong Gede	357	High
3		Caringin	419	Very High
4		Ciawi	394	High
5		Cibinong	301	High
6		Cisarua	385	High
7		Megamendung	384	High
8	East	Cariu	46	Low
9		Cileungsi	160	Medium
10		Citeureup	160	Medium
11		Gunung Putri	176	Medium
12		Jonggol	91	Low
13		Klapanunggal	88	Low
14		Sukamakmur	143	Low
15		Sukaraja	319	High
16		Tanjungsari	73	Low

Based on Table 4 above, the population density in Bogor Regency in 2018 was measured using a grid size of 100 x 100 m², equivalent to 1 hectare. The analysis revealed that the highest population density was found in Caringin District, categorized as Very High Density, with a density value of 419 persons per hectare. The calculation was performed by dividing the total population in each sub-district by the total built-up area, which was derived from the dasymetric mapping process. This ensures that the resulting density values (expressed in persons per hectare) consistently reflect the actual distribution of the population within urbanized areas rather than the entire administrative area. Maintaining the unit "persons/Ha" throughout the analysis allows for accurate comparison across sub-districts and time periods.

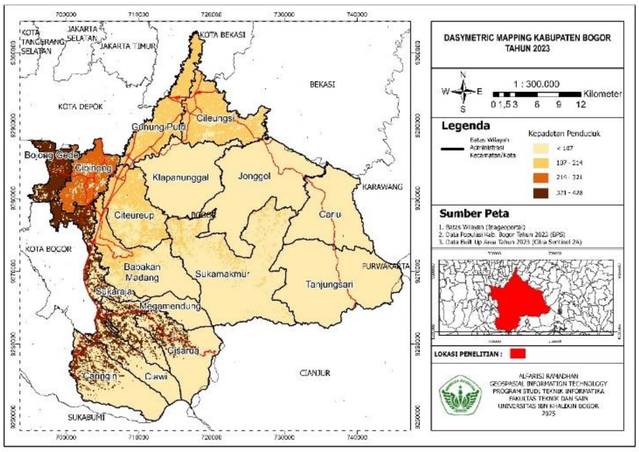

Figure 9 Layout Dasymetric Mapping of Bogor Regency in 2023

The population density values, expressed in persons per hectare (persons/ha), calculated in ArcGIS using the Calculate Geometry tool, can be seen in Table 5

Table 5 Population Density Values by District in Bogor Regency in 2023

No.	Sub-District Name	Population Density (persons/Ha)	Population Density Classification
1	Babakan Madang	129	Low
2	Bojong Gede	388	High
3	Caringin	427	Very High
4	Cariu	47	Low
5	Ciawi	404	Very High
6	Cibinong	304	High
7	Cileungsi	162	Medium
8	Cisarua	362	High
9	Citeureup	192	Medium
10	Gunung Putri	180	Medium
11	Jonggol	95	Low
12	Kelapa Nunggal	90	Low
13	Megamendung	387	High
14	Sukamakmur	154	Medium
15	Sukaraja	324	High
16	Tanjungsari	74	Low

Based on Table 5 above, the population density in Bogor Regency in 2018, as analyzed through dasymetric mapping, shows that the highest density was observed in Caringin District, with a value of 419 persons per hectare, categorized as very high. Meanwhile, according to Table 5, the population density in Caringin District increased to 427 persons per hectare in 2023, maintaining its classification as very high within Bogor Regency. The graph illustrating the increase in population density in Bogor Regency for the years 2018 and 2023 can be seen in Figure 10.

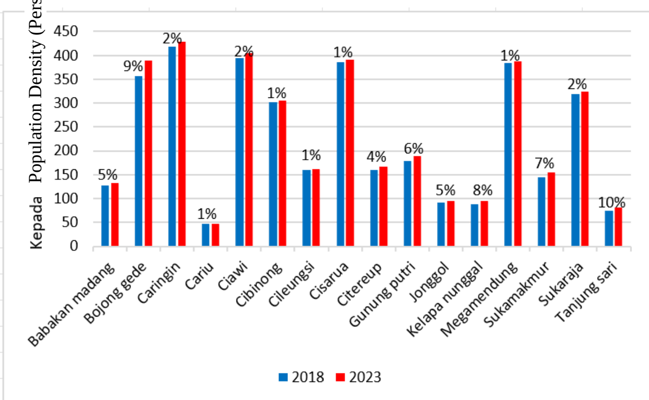

Figure 10 graph illustrating the increase in population density in Bogor Regency for the years 2018 and 2023

As shown in Figure 10, the population density in Bogor Regency increased in each district between 2018 and 2023. The highest density was observed in Caringin District, which experienced a 2% increase, from 419 persons per hectare in 2018 to 428 persons per hectare in 2023.

C. *Result Analysis Air Pollution*

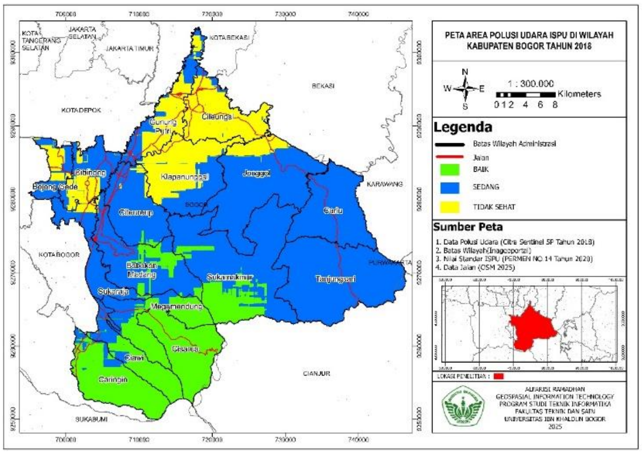

Figure 11 Affected Area by Air Pollution Based on ISPU Classes in 2018

The area affected by air pollution in each district, measured in hectares (Ha) and calculated using the Calculate Geometry tool in ArcGIS, is presented in Table 6

Table 6 Air Pollution Extent by District in Bogor Regency in 2018

NO	Wilayah Kabupaten Bogor	Nama Kecamatan	Luas Kecamatan (Ha)	Luas Polusi Udara Kelas ISPU (Ha)			Total Persentase (%)		
				Baik	Sedang	Tidak Sehat	Baik	Sedang	Tidak Sehat
1.	Tengah	Babakan Madang	9.161,79	1.805,93	7.266,74	89,12	20	79	1
2.		Bojong Gede	2.747,30	-	1.698,48	1048,82	-	62	38
3.		Caringin	7.790,61	7.089,67	700,94	-	91	9	-
4.		Ciawi	4.706,73	3.214,20	1.492,53	-	68	32	-
5		Cibinong	4.665,19	-	2.788,83	1.876,36	-	60	40
6		Cisarua	7.106,34	7.106,34	-	-	100	-	-
7.		Megamendung	6.344,39	4.526,18	1.818,21	-	71	29	-
8.	Timur	Cariu	8.485,67	-	8.485,67	-	-	100	-
9.		Cileungsi	7.015,96	-	3.57,73	6.658,23	-	5	95
10.		Citereup	6.933,28	181,67	6.428,15	323,46	3	93	5
11.		Gunung Putri	6.093,44	-	2.287,78	3.805,66	-	38	62
12.		Jonggol	13.541,42	1,02	11.928,47	1.611,93	-	88	12
13.		Klapanunggal	9.589,36	-	3.504,37	6.084,99	-	37	63
14.		Sukamakmur	18.207,54	4.161,92	14.045,62	-	23	77	-
15.		Sukaraja	4.386,97	64,50	3.902,75	419,71	1	89	10
16.		Tanjungsari	14.735,38	9,70	14.725,69	-	-	100	-
Luas Total Polusi Udara di Kabupaten Bogor (Ha)			131.511,39	28.161,11	81.431,90	21.918,22			

Based on Table 6 above, the total area affected by air pollution in Bogor Regency in 2018 was 131,511.39 hectares. The analysis shows that the largest portion of the polluted area falls under the Moderate category, covering 81,431.97 hectares, which accounts for approximately 62% of the total polluted area in Bogor Regency in 2018. Further analysis of the air pollution extent by district was conducted using classifications based on the Air Pollution Standard Index (ISPU), which includes five categories: (1) Healthy, (2) Moderate, (3) Unhealthy, (4) Very Unhealthy, and (5) Hazardous. For example, based on the 2018 air pollution analysis in Bogor Regency, three categories were identified. Gunung Putri District was found to be in the Unhealthy category, as shown in Figure 12.

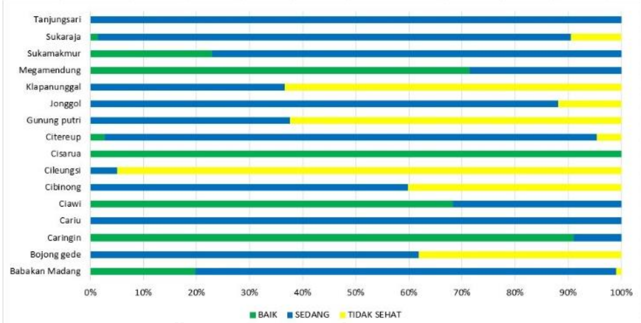

Figure 12 Air Pollution (ISPU) Conditions in Bogor Regency in 2018

As shown in Figure 12, the air pollution level in Bogor Regency in 2018 was predominantly classified as "Moderate," accounting for 62% of the total polluted area in the regency. Seven out of sixteen districts had the highest classification in the "Moderate" category, namely Cibinong, Bojonggede, Babakan Madang, Citereup, Cariu, Jonggol, Sukaraja, and Tanjungsari.

In the "Good" classification, four districts recorded the highest classification: Caringin, Ciawi, Cisarua, and Megamendung. The total area classified as "Good" air quality in Bogor Regency in 2018 was 28,161.13 hectares, representing approximately 21% of the total polluted area.

For the "Unhealthy" classification in 2018, which covered 17% or 21,918.29 hectares, three districts had the highest pollution levels: Klapanunggal with 63%, Gunung Putri with 62%, and Cileungsi with 95% of their respective district areas classified as unhealthy within Bogor Regency.The layout of the map showing areas affected by air pollution, classified according to the Air Pollution Standard Index (ISPU) in Bogor Regency in 2023, can be seen in Figure 13.

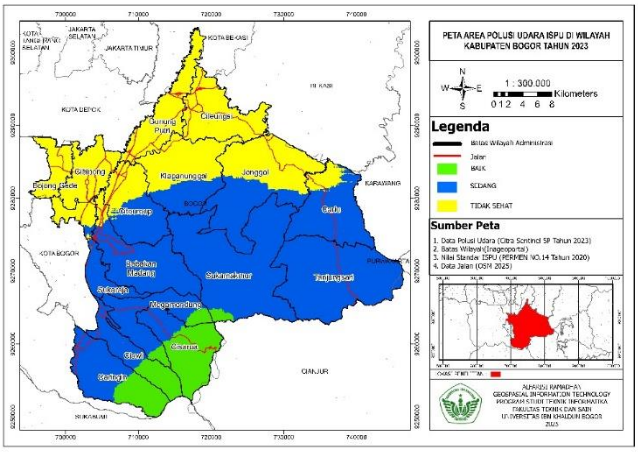

Figure 13 Map of Areas Affected by Air Pollution Based on ISPU Classes in 2023

The area affected by air pollution in each district of Bogor Regency, measured in hectares (Ha) and calculated using the Calculate Geometry tool in ArcGIS, is presented in Table 7.

Table 7 Air Pollution Extent by District in Bogor Regency in 2018

NO	Wilayah Kabupaten Bogor	Nama Kecamatan	Luas Kecamatan (Ha)	Luas Polusi Udara Kelas ISPU (Ha)			Total Persentase (%)		
				Baik	Sedang	Tidak Sehat	Baik	Sedang	Tidak Sehat
1.	Tengah	Babakan Madang	9.161,79	-	8.515,14	646,65	-	93	7
2.		Bojong Gede	2.747,46	-	-	2.747,46	-	-	100
3.		Caringin	7.790,67	2.720,62	5.070,05	-	35	65	-
4.		Ciawi	8.485,67	-	7.149,38	1.336,29	-	84	16
5.		Cibinong	4.706,94	1.971,14	2.735,80	-	42	58	-
6.		Cisarua	7.106,44	5.209,75	1.896,69		73	27	-
7.		Megamendung	6.344,39	1.124,72	5.219,67	-	18	82	-
8.	Timur	Cariu	8.485,67	-	7.149,38	1.336,29	-	84	16
9.		Cileungsi	7.015,72	-	-	7.015,72	-	-	100
10.		Citereup	6.933,28	-	4.056,47	2.876,82	-	59	41
11.		Gunung Putri	6.093,49	-	-	6.093,49	-	-	100
12.		Jonggol	13.541,70	-	6.256,28	7.285,42	-	46	54
13.		Klapanunggal	9.589,36	-	3.228,53	6.360,83	-	34	66
14.		Sukamakmur	18.207,59	447,44	1.7760,15	-	2	98	-
15.		Sukaraja	4.386,92	-	2.678,97	1.707,95	-	61	39
16.		Tanjungsari	14.735,20	-	14.735,20	-	-	100	-
Luas Polusi Udara di Kabupaten Bogor (Ha)			131.511,72	11.473,67	79.302,32	40.735,73	-	-	-

Based on Table 7 above, the total area affected by air pollution in Bogor Regency in 2018 was 131,511.72 hectares. The highest extent of the "Unhealthy" classification was found in Gunung Putri District, with an area of 3,805.66 hectares, accounting for approximately 62% of the total polluted area in the district. In comparison, according to Table 7, the air pollution classification in Gunung Putri District in 2023 showed a 100% increase in polluted area, reaching 6,093.49 hectares. This is illustrated in Figure 14

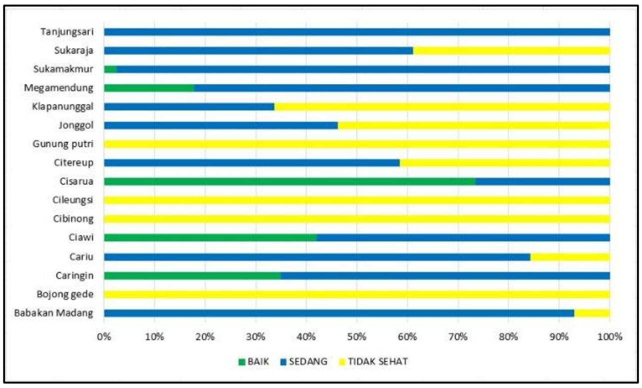

Figure 14 Air Pollution (ISPU) Conditions in Bogor Regency in 2018

As shown in Figure 14, the air pollution level in Bogor Regency in 2023 was predominantly classified as "Moderate," accounting for 60% of the total polluted area in the regency. Seven out of sixteen districts had the highest classification in the "Moderate" category, namely Cibinong, Bojonggede, Babakan Madang, Citereup, Cariu, Jonggol, Sukaraja, and Tanjungsari.

In the "Good" classification, four districts recorded the highest classification: Caringin, Ciawi, Cisarua, and Megamendung. The total area classified as "Good" air quality in Bogor Regency in 2023 was 11,473.67 hectares, representing approximately 9% of the total polluted area.

For the "Unhealthy" classification, there was an increase in the polluted area by 31%, covering 40,735.73 hectares. Three districts had the highest pollution levels: Klapanunggal with 66%, Gunung Putri with 100%, and Cileungsi with 100% of their respective district areas classified as unhealthy within Bogor Regency in 2023. The graph illustrating the increase in air pollution by district based on ISPU classification values for 2018 and 2023 in East Bogor Regency can be seen in Figure 15.

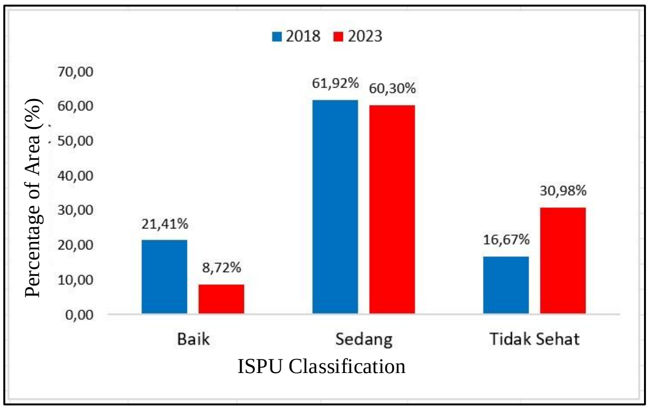

Figure 15 Trend of Increasing Area by ISPU Classification in Bogor Regency in 2018 and 2023

As shown in Figure 15, the air pollution classifications in Bogor Regency for the years 2018 and 2023 consist of three categories: Good, Moderate, and Unhealthy. The area classified as Good decreased by 59%, from 21.41% in 2018 to 8.72% in 2023. The Moderate classification also saw a slight decrease of 3%, from 61.92% in 2018 to 60.30% in 2023. Conversely, the Unhealthy classification experienced an 86% increase, rising from 16.67% in 2018 to 30.98% in 2023, relative to the total polluted area in Bogor Regency in 2023. These decreases and increases in air pollution are attributed to the expansion of polluted areas over the five-year period.

D. Comparison of Air Pollution Model Results with Field ISPU Data

Validation was conducted to determine the accuracy level of air pollution distribution obtained from Sentinel-5P satellite imagery. The validation used air pollution point data from the Environmental Agency (DLH), consisting of 12 points in 2023 and 7 points in 2018, all distributed across Bogor Regency. Figures 16–17 show the plotted points of field checks distributed within the air pollution areas in Bogor Regency.

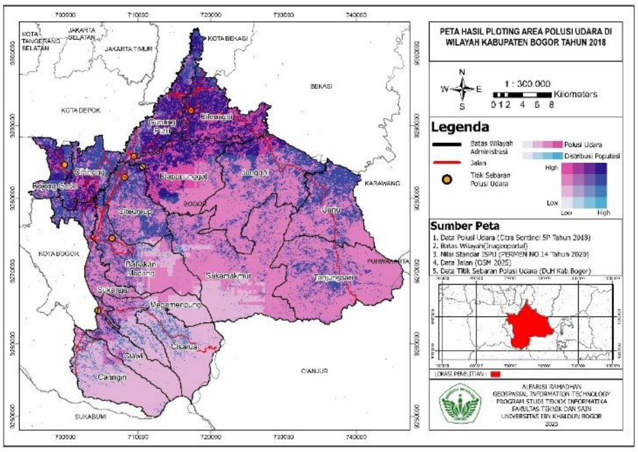

Figure 16 Plotting of Field Check Points in 2018

The distribution of air pollution points obtained from the Environmental Agency of Bogor Regency was processed in ArcGIS Pro using the "Export Values to Point" tool to extract air pollution values from Sentin el-5P imagery for each parameter. The results are presented in Table 8

Table 8 Distribution of Points from the Environmental Agency and Sentinel-5P Imagery in 2018

No	Coordinate Point		DLH Air Pollution Value (µg/m^3)			*Sentinel-5p* Air Pollution Value (Mol/m^2)		
	X	Y	*SO_2*	*NO_2*	*CO*	*SO_2*	*NO_2*	*CO*
1.	106,90259	-6,474847	17,33	51,3	344	0,000024	0,000112	0,0011628
2.	106,892015	-6,462145	34,99	9,4	458	0,000056	0,0000161	0,0016333
3.	106,962778	-6,404722	35,2	17,12	344	0,000113	0,0000336	0,0012193
4.	106,865215	-6,564139	60,22	5,68	344	0,000132	0,0000087	0,00123
5.	106,847821	-6,653975	70,73	4,41	344	0,000123	0,0000056	0,0012157
6.	106,880653	-6,487972	86	8,26	344	0,000136	0,0000176	0,0011577
7.	106,80571	-6,473001	106,12	3,13	344	0,00016	0,0000101	0,0011943

Table 9 Converted Values of Sentinel-5P Imagery in 2018

No	DLH Air Pollution Value (µg/m^3)			*Sentinel-5p* Air Pollution Value (µg /m^3)		
	SO_2	*NO_2*	*CO*	*SO_2*	*NO_2*	*CO*
1.	17,33	51,3	344	15,36	51,52	325,58
2.	34,99	9,4	458	35,84	7,41	457,32
3.	35,2	17,12	344	72,32	15,46	341,40
4.	60,22	5,68	344	84,48	4,00	344,40
5.	70,73	4,41	344	78,72	2,58	340,40
6.	86	8,26	344	87,04	8,10	324,16
7.	106,12	3,13	344	102,4	4,65	334,40

Based on Table 9, the results of unit conversion for the concentrations of NO_2, SO_2, and CO are presented. The converted values show good agreement with the concentration measurements conducted by the Environmental Agency, as indicated by the relatively small average differences between the datasets. This suggests that the conversion method applied is reliable and consistent with field observations

Furthermore, several validation tests were performed to assess the accuracy and reliability of the converted data. Among these tests are the Root Mean Square Error (RMSE) and the Mean Absolute Error (MAE). RMSE quantifies the average magnitude of the errors between the converted satellite-derived concentrations and the ground-based measurements, providing an objective metric to evaluate the performance of the conversion process. Meanwhile, MAE measures the average absolute difference between the predicted and observed values, offering a straightforward interpretation of the average error magnitude without emphasizing larger errors disproportionately. Together, these metrics provide a comprehensive assessment of the conversion accuracy and data quality.Here are the results of the air pollution accuracy test in Bogor Regency for 2018, which can be seen in the Table 10.

Table 10 Accuracy Test Results of Air Pollution in 2018

Air Pollution Parameter	*RMSE* (µg/m^3)	*MAE* (µg/m^3)
CO	10,989	7,876
SO_2	17,112	10,992
NO_2	1,478	1,295

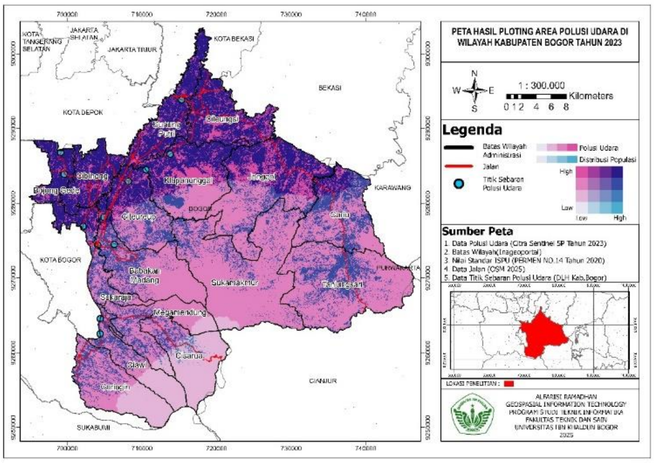

Figure 17 Plotting of Field Check Points in 2023

The distribution of air pollution points obtained from the Environmental Agency of Bogor Regency was processed in ArcGIS Pro using the "Export Values to Point" tool to extract air pollution values from Sentin el-5P imagery for each parameter. The results are presented in Table 11

Table 11 Spatial Distribution of Points from the Environmental Agency and Sentinel-5P Imagery in 2023

No.	Coordinate Point		DLH Air Pollution Value (µg/m³)			*Sentinel-5p* Air Pollution Value (Mol/m²)		
	X	Y	SO_2	NO_2	*CO*	SO_2	NO_2	*CO*
1.	106,8474	-6,6727	61,6	31,7	1489	0,000109	0,000051	0,00532
2.	106,847433	-6,654258	58	40,9	1948	0,000106	0,000085	0,00694
3.	106,8264	-6,54268	57,8	39,4	1946	0,000084	0,000094	0,00693
4.	106,79891	-6,45344	58,2	38,8	2177	0,000107	0,000081	0,007753
5.	106,803208	-6,479775	58,5	43,7	1833	0,000105	0,000092	0,006536
6.	106,851414	-6,53155	57,9	42,9	1718	0,000104	0,000091	0,00613
7.	106,97673	-5,64035	60,8	31,8	1833	0,000109	0,000055	0,00654
8.	106,944983	-6,389217	62,4	23,5	1146	0,000102	0,00006	0,0041
9.	106,931425	-6,454992	59,6	28,2	<1145	0,000097	0,00007	0,004
10.	106,880761	-6,487872	61,3	25,4	1260	0,0001	0,000057	0,0046
11.	106,864092	-6,564589	59,2	22,5	<1145	0,000105	0,000079	0,0041
12.	106,844039	-6,565564	58,2	31	1375	0,000102	0,000084	0,004894

Table 12 Converted Values of Sentinel-5P Imagery in 2018

No	DLH Air Pollution Value (µg/m³)			*Sentinel-5p* Air Pollution Value (µg /m³)		
	SO_2	NO_2	*CO*	SO_2	NO_2	*CO*
1.	61,6	31,7	1489	69,76	23,46	1490
2.	58	40,9	1948	67,84	39,1	1943
3.	57,8	39,4	1946	53,76	43,24	1940
4.	58,2	38,8	2177	68,48	37,26	2171
5.	58,5	43,7	1833	67,2	42,32	1830
6.	57,9	42,9	1718	66,56	41,86	1716
7.	60,8	31,8	1833	69,76	25,3	1831
8	62,4	23,5	1146	65,28	27,6	1148
9	59,6	28,2	<1145	62,08	32,2	1120
10	61,3	25,4	1260	64	26,22	1288
11	59,2	22,5	<1145	67,2	36,34	1148
12	58,2	31	1375	65,28	38,64	1370

Here are the results of the air pollution accuracy test in Bogor Regency for 2023, which can be seen in the Table 13

Table 13 Accuracy Test Results of Air Pollution in 2023

Air Pollution Parameter	*RMSE* (µg/m³)	*MAE* (µg/m³)
CO	11,368	7,18
SO_2	7,372	6,815
NO_2	5,894	4,561

E. Spatial Distribution Pattern Model of Air Pollution (ISPU) in Bogor Regency in 2018 and 2023

The spatial model produced represents the field conditions in the form of spatial distribution patterns of pollutants derived using remote sensing techniques. The pollutant spatial distribution models for the years 2018 and 2023 exhibit a similar pattern. In 2018, the dominant air pollution concentration in Bogor Regency fell within the moderate classification, covering an area of 103,426.57 hectares, which was widely distributed across industrial zones, residential areas, as well as the southwestern and northern parts of the regency. In 2018, there were two classification categories: good and moderate, with the moderate class being predominant.By 2023, three classification categories were identified: good, moderate, and unhealthy. Notably, there was an increase in the area classified as unhealthy, expanding to 40,735.73 hectares distributed throughout Bogor Regency. The spatial distribution pattern models of air pollution in Bogor Regency are illustrated in the following Figure 18-19.

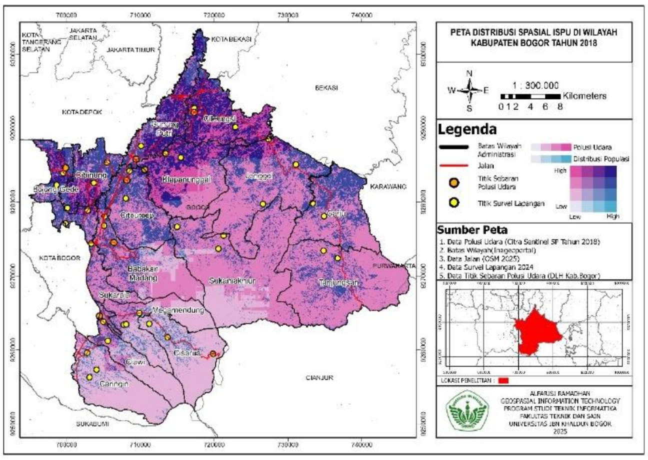

Figure 18 Spatial Distribution Map of the Air Quality Standard Index (ISPU) in Bogor Regency for the Year 2018

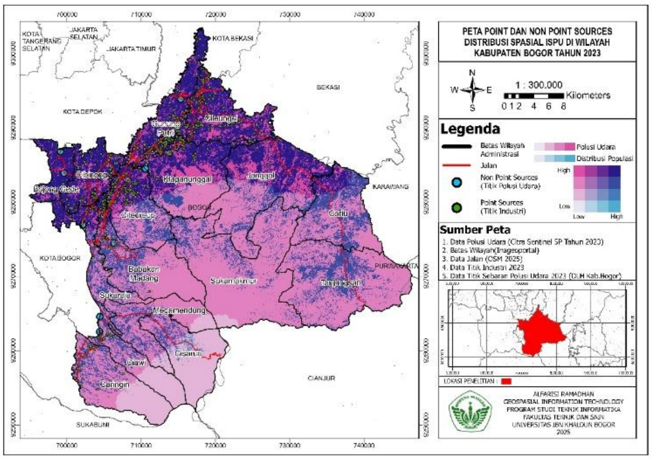

Figure 19 Spatial Distribution Map of the Air Quality Standard Index (ISPU) in Bogor Regency for the Year 2023

The area affected by air pollution, measured in hectares (Ha), was calculated using the Calculate Geometry tool in ArcGIS. The results can be seen in Table 14

Table 14 Area Affected by Air Pollution in 2018 Measured in Hectares (Ha) Calculated Using ArcGIS Calculate Geometry Tool

No	Classification	Air Pollution Area (Ha)	Percentage (%)
1.	Good	28.161,13	21%
2.	Moderate	81.431,97	62%
3.	Unhealthy	21.918,29	17%
	Total Area	131.511,39	100%

Table 14 above shows that in 2018, the total area of Bogor Regency was 131,511.54 hectares. This area is divided into three classes: Good, covering 28,084.97 hectares; Moderate, covering 103,426.57 hectares; and Unhealthy, covering 21,918.29 hectares. It can also be observed that the Moderate class has the highest percentage in Bogor Regency, accounting for approximately 62%.

The area affected by air pollution, measured in hectares (Ha), was calculated using the Calculate Geometry tool in ArcGIS. The results can be seen in Table 15.

Table 15 Area Affected by Air Pollution in 2023 Measured in Hectares (Ha) Calculated Using ArcGIS Calculate Geometry Tool

No	Classification	Air Pollution Area (Ha)	Percentage (%)
1	Good	11.473,67	9%
2	Moderate	79.302,32	60%
3	Unhealthy	40.735,73	31%
	Total Area	131.511,72	100%

Table 15 above shows that in 2023, the total area of Bogor Regency was 131,511.72 hectares. This area is divided into three classes: Good, covering 11,473.67 hectares; Moderate, covering 79,302.32 hectares; and Unhealthy, which has the highest percentage in Bogor Regency, accounting for approximately 31%.

F. Integration of Spatial Distribution Pattern Models of Air Pollution with Point Sources and Non-Point Sources

The integration of the air pollution model was carried out to differentiate pollution sources based on their characteristics, namely point sources and non-point sources. Point sources of air pollution originate from industrial activities, while non-point sources stem from motor vehicle emissions, producing pollutants such as Carbon Monoxide (CO), Nitrogen Dioxide (NO_2), and Sulfur Dioxide (SO_2). The map of point sources and non-point sources in the spatial distribution pattern model of air pollution in Bogor Regency illustrates industrial points scattered throughout the region, which are factors contributing to the increase in air pollution. This can be seen in Figure 20.

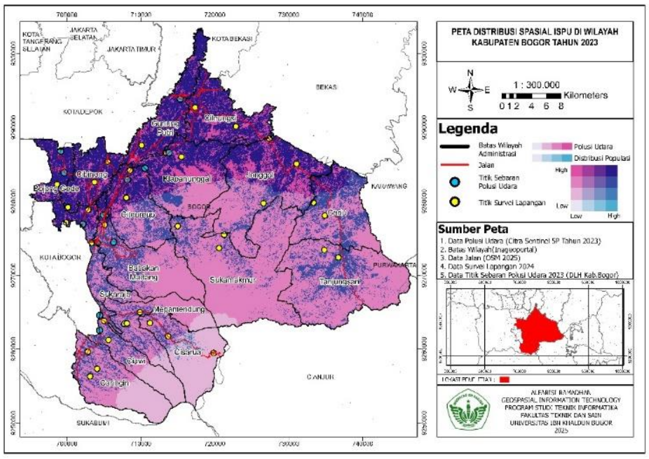

Figure 20 Map of Point and Non-Point Sources in the Spatial Distribution of ISPU in Bogor Regency, 2023

In interpreting the ISPU map, each pollution category is clearly represented with standardized colors according to the legend. For example, dark purple shading indicates areas classified as "Hazardous" with ISPU values above 300, while red and orange areas represent "Unhealthy" and "Moderate" categories with ISPU values ranging from 101–200 and 51–100 respectively. Including a detailed legend and quantitative labels ensures that the map effectively communicates the spatial variation of air quality levels and their implications for public health risk.

Based on Figure 20, air pollution sources in Bogor Regency can be classified into two main categories: point sources and non-point sources. Point sources refer to air pollution originating from industrial activities that are concentrated at specific locations. According to the spatial distribution map, point sources in Bogor Regency are concentrated in the northern and eastern regions, particularly in Gunung Putri, Cibinong, and Citeureup Districts. These areas are known as the main industrial zones in Bogor Regency, where manufacturing and heavy industry activities significantly contribute to pollutant emissions into the atmosphere.

Meanwhile, non-point sources are air pollution sources derived from dispersed activities, such as motor vehicle emissions. The primary pollutants produced by these non-point sources include Carbon Monoxide (CO), Nitrogen Dioxide (NO_2), and Sulfur Dioxide (SO_2). Data on pollutant concentrations were obtained from monitoring conducted by the Environmental Agency (Dinas Lingkungan Hidup, DLH) of Bogor Regency. Non-point sources generally follow major transportation routes and areas with high population density, as shown on the map illustrating air pollution distribution along main road corridors and densely populated regions.

The spatial distribution map of the Air Quality Standard Index (ISPU) for 2023 indicates that areas with industrial concentrations (point sources) tend to exhibit higher levels of air pollution, marked by dark purple shading on the map. Conversely, pollution dispersion from non-point sources is also significant in areas with heavy vehicular traffic, especially along primary inter-district roadways. The number of industrial points in each district can be seen in Table 16.

Based on Table 16, the distribution of industrial points in Bogor Regency exhibits a significant concentration pattern in the eastern region, particularly in the districts of Gunung Putri, Cileungsi, and Citeureup, which collectively account for approximately 29% of the total industrial points.

Table 16 Number of Industrial Points in Each District of Bogor Regency

NO	Bogor Regency Area	Sub-District	Number of Industrial Points	Percentage
1.	Central	Babakan Madang	66	8 %
2.		Bojong Gede	4	1%
3.		Caringin	25	3%
4.		Ciawi	18	2%
5.		Cibinong	86	11%
6	East	Cileungsi	147	19%
7.		Citereup	116	15%
8.		Gunung Putri	227	29%
9.		Jonggol	4	1%
10.		Klapanunggal	59	8%
11.		Sukaraja	25	3%

This indicates strong industrial activity in these areas, likely driven by factors such as the availability of infrastructure, transportation accessibility, and spatial planning policies that support the development of industrial zones. In contrast, the central regions, such as Bojong Gede and Jonggol, have a very low number of industrial points. The condition of industrial points is also illustrated by the pie chart shown in Figure 21.

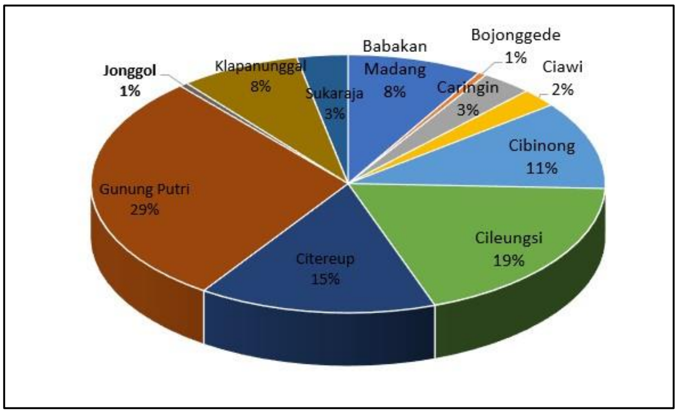

Figure 21 Condition of Industrial Points in the Bogor Regency Area

IV. CONCLUSION

Based on the results of the urban growth analysis in Bogor Regency between 2018 and 2023, there was a significant increase observed. Gunung Putri sub-district experienced the highest growth, with an increase of 16%. The built-up area expanded from 4,393.30 hectares in 2018 to 5,113.65 hectares in 2023. Accuracy assessment of the model demonstrated excellent performance, with an overall accuracy of 92.5% and a kappa coefficient of 0.83.

The dasymetric mapping results for Bogor Regency from 2018 to 2023 also showed a notable increase in population density. Gunung Putri sub-district recorded an increase of

6%, with a population density rising from 178 inhabitants per hectare in 2018 to 180 inhabitants per hectare in 2023.

Consequently, air pollution levels increased during this period. In 2018, three air quality classes were identified: good (28,161.13 hectares), moderate (81,431.97 hectares), and unhealthy (21,918.29 hectares). By 2023, the classification areas changed to good (11,473.67 hectares), moderate (79,302.32 hectares), and unhealthy (40,735.73 hectares), representing an 86% increase in the unhealthy classification area between 2018 and 2023. The mean absolute error (MAE) values ranged from 1.295 µg/m³ to 10.992 µg/m³, while the root mean square error (RMSE) values ranged from 1.478 µg/m³ to 17.112 µg/m³. The best MAE value was 1.295 µg/m³, indicating the average absolute difference between the predicted results and the data from the Bogor Regency Environmental Agency. Meanwhile, the best RMSE value was 1.478 µg/m³. "These relatively low MAE and RMSE values suggest that the air pollution estimation model has high reliability and aligns well with related studies that report acceptable RMSE values for air quality predictions typically ranging between 1 and 20 µg/m³ [18], [19]." This indicates that the model's predictions are accurate enough for supporting spatial decision-making and local air quality management strategies.

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