Konya Mühendislik Bilimleri Dergisi, c. 11, s. 4, 1035-1046, 2023
Konya Journal of Engineering Sciences, v. 11, n. 4, 1035-1046, 2023
ISSN: 2667-8055 (Electronic)
DOI: 10.36306/konjes.1333625

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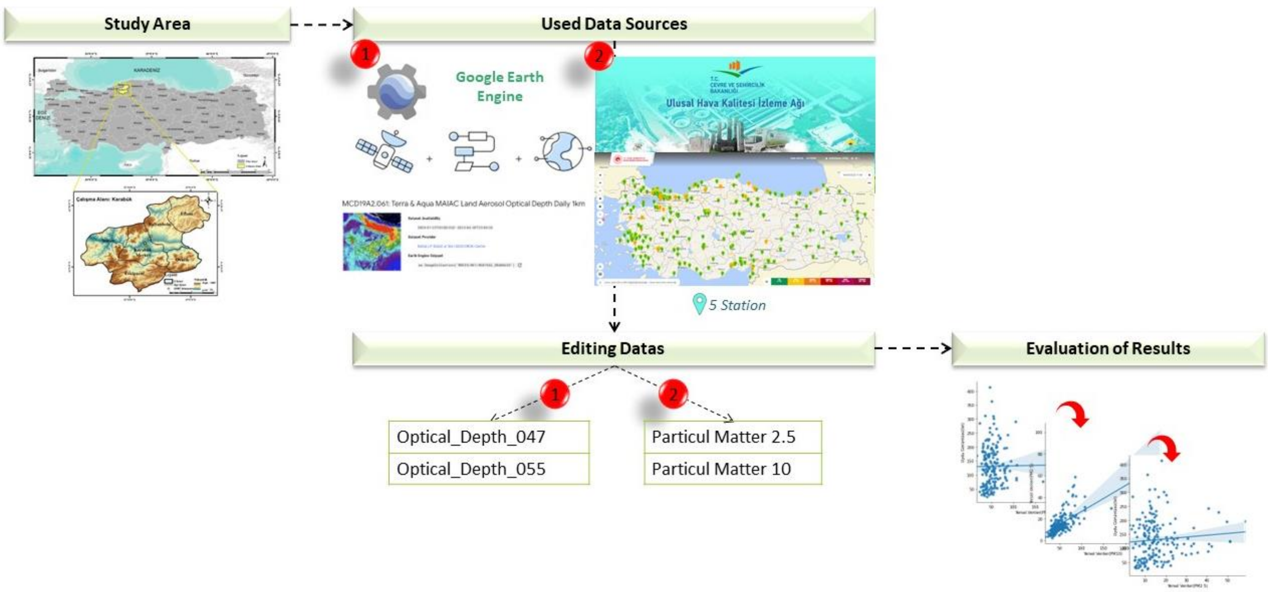
Highlights

- Investigation of aerosol optical depth from ground-based stations and satellite images, analysis and evaluation of results
- Positional examination of blue and green land surface bands from MODIS satellite
- Temporal analysis of PM2.5 and P10 data from National Air Quality Monitoring Stations

Graphical Abstract (Optional)



Flowchart

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(Received: 27.07.2023; Accepted in Revised Form: 24.09.2023)

ABSTRACT: The concept of aerosol refers to the combination of microscopic solid or liquid particles present in the atmosphere along with a mixture of gases. These particles are suspended in the air at different sizes and are evaluated based on their ability to scatter or absorb light, which is quantified through a measurement known as aerosol optical depth. These particles' quantities are determined using specialized devices, commonly referred to as "aerosol optical depth meters" or "optical thickness meters." Additionally, through remote sensing technology, aerosol optical depth can also be measured via satellites.

In this study, aerosol optical depth has been examined temporally and spatially in the Karabük province for 2022. For this aim, data from National Air Quality Monitoring Stations (NAQMS) situated nationwide was employed, along with MODIS satellite images. Data from five stations in Karabük province, namely Kardemir1, Kardemir2, Tören Alanı, 75.yıl, and Safranbolu, were used for temporal analysis, while satellite imagery was used for spatial analysis. The relationship between aerosol optical depths derived from MODIS satellite data using green and blue band information and station data was investigated. As a result, a 99% positive correlation was found between the two bands obtained from the MODIS satellite, and a significant correlation was observed between ground-based particulate matter 2.5(PM2.5) and particulate matter 10 (PM10) data. Data from the Tören Alanı station, which had a higher amount of data (357 days) compared to other stations, was used to determine this correlation. It was found that there was an 86.35% positive correlation among particulate matters. A moderate correlation was also identified between ground-based data and aerosol optical depth obtained from satellite imagery.

Keywords: *Aerosol optical depth, Air quality, Google earth engine, MODIS sensor, Particulate matter*

1. INTRODUCTION

Within the Earth's atmosphere, diverse gases exist in various ratios. Moreover, aerosols, formed by the suspension of solid and liquid particles in a gaseous phase, are also present. [1]. Aerosols with particle sizes ranging from 2.5 to 10 μm are commonly used as a parameter to assess air quality. High aerosol optical depth indicates increased particulate matter pollution in the air. These particles can originate from various natural or human activities and become mixed into the atmosphere [2]. For instance, natural sources include volcanic eruptions [3], forest fires [4, 5, 6], soil or desert dust [7, 8]. At the same time, human-induced factors comprise industrial activities [9], emissions from vehicles [10], and the combustion of fuels used for heating in homes [11].

Various reasons lead to forming these tiny particles, which can linger in the atmosphere for long periods and be transported in different directions by the wind [12, 13]. With sizes ranging from a few nanometers to a few micrometers, these structures can cause short-term effects such as nasal and eye irritation in the human body, and they can also penetrate deep into the lungs [14]. As a result, they can reduce visibility. These tiny particles also impact on lung function, leading to respiratory problems such as respiratory tract diseases [15]. Additionally, changes in aerosols in the air can influence the heating and cooling processes, altering the thermal state of the atmosphere. This has contributed to the recent changes we have been experiencing in the climate [16]. Aerosols directly and indirectly, affect regional and global

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climate change [17-19]. Therefore, monitoring air quality and taking necessary measures are essential.

Turkey's Ministry of Environment, Urbanization, and Climate Change have established national air quality monitoring stations in urban centers, industrial areas, and regions with heavy transportation lines to achieve this goal. As of 2022, there are a total of 365 stations throughout Turkey [20]. The air quality index is calculated using data obtained from these stations, which includes measurements of particulate matter (PM10, PM2.5), carbon monoxide (CO), sulfur dioxide (SO2), nitrogen dioxide (NO2), and ozone (O3). Additionally, free access to this data is provided through a website [21]. However, there are some limitations in ground-based observation data due to deficiencies and the limited number of stations in certain locations. Insufficient station points make determining air quality over a large area challenging. While the number of stations can be increased, it is not a definitive or cost-effective solution.

In addition to ground-based stations, remote sensing technology allows the detection and monitoring of aerosols in the atmosphere through Aerosol Optical Depth (AOD) measurements using various satellites [22]. Satellites such as The Moderate Resolution Imaging Spectroradiometer (MODIS) Terra and Aqua, Ozon Monitoring Instrument (OMI Aura), Visible Infrared Imaging Radiometer Suite (VIIRS Suomi NPP), and Sentinel-5P (TROPOMI) are used for this purpose. The Sentinel-5 TROPOMI satellite is preferred for the detection and monitoring of various gases in the atmosphere using satellite imagery. The preferred satellite for the detection and monitoring of various gases in the atmosphere, as well as for examining NO2 and CO emissions in a metropolitan city [23], establishing the relationship between CO and NO2 pollutants in the Western Black Sea region using the UV_AER index [24], investigating the health impact of CO emissions in the Iran region [25], evaluating NO2 and CO pollutants in terms of geography and population [26], determining the temporal and spatial distribution of CH4, NO2, O3, and CO emissions and identifying factors contributing to their increase in pollution[27] in various studies, is the Sentinel-5 satellite. For aerosol optical depth data, the Terra and Aqua satellites of the MODIS satellite system, which provide daily data, are preferred [28]. This satellite is preferred due to its proven effectiveness in providing global and regional results [29, 30].

This study obtained aerosol optical depth (AOD) data for 2022 in Karabük, one of Turkey's significant iron and steel industry cities. The aerosol optical values in Karabük were analyzed both spatially and temporally. For this purpose, data from five stations located within the region (Kardemir1, Kardemir2, Tören Alanı, 75.yıl, and Safranbolu) were used, which were established to monitor air quality within the country. Additionally, MODIS satellite images were used to examine aerosol values in other parts of the region. The Terra and Aqua systems were chosen due to their ability to provide data twice a day and their common usage in the literature. The acquisition and processing of satellite images were done using the Google Earth Engine (GEE) platform. Both types of data were analyzed, and their results were compared. The aim of this study is to analyze and interpret air quality not only on a point basis but also spatially. In this context, the sources responsible for the increase in pollution levels can be identified, or it can contribute to the more effective management of air quality.

2. MATERIAL AND METHODS

2.1. Study Area

The study area is located in northern Turkey's Western Black Sea region. It focuses explicitly on the province of Karabuk, situated at an elevation of 270 meters ab.ove sea level (Figure 1). Based on the data from the address-based population registration system as of December 31, 2021, the population of Karabuk is 249,287 The province's largest settlement and central district is Karabük, and the other districts include Eflani, Eskipazar, Ovacik, Safranbolu, and Yenice [31]. The historical, natural beauty and cultural architecture make the province rich, with its historic houses in the Safranbolu district listed as a UNESCO World Heritage site. Moreover, economically speaking, Karabuk is one of Turkey's significant provinces in terms of industry. It houses several factories and industrial facilities, primarily focused on steel, mining, and iron-steel sectors. Establishing the first facilities in 1937 transformed the province into an industrial city. The data and workflow diagram used in the study are given in Figure 2.

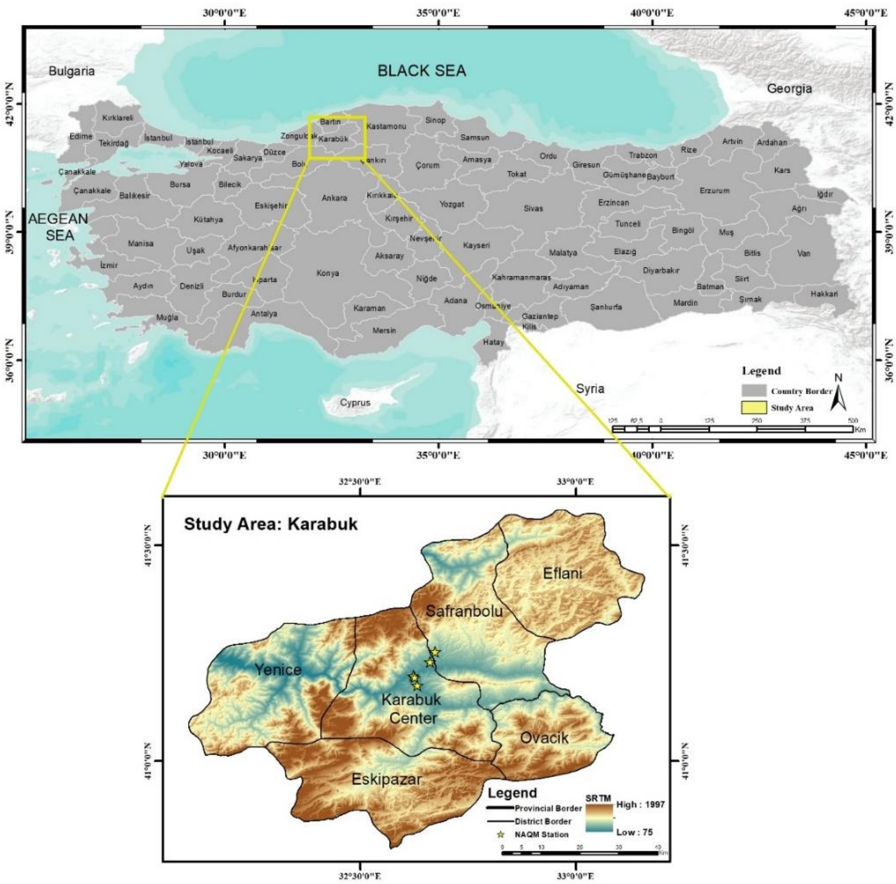

Figure 1. Using SRTM-DEM, visual representations of the study area, Karabuk, and the ground stations are presented

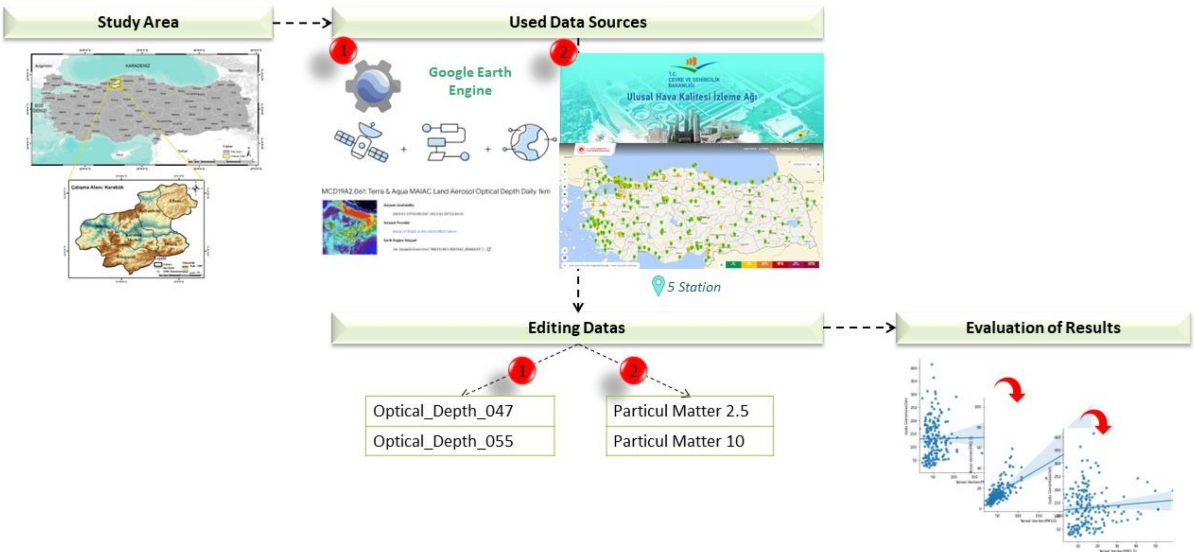

Figure 2. Work-flow diagram.

2.2. Used Data

Aerosol optical depth (AOD) is a parameter used to gauge the extent to which aerosols in the atmosphere scatter or absorb light of a particular wavelength along a given path. As it is a unitless quantity, it is denoted by the symbol "tau (τ)" in the literature [32, 33]. Typically, AOD values range between 0 and infinity. These values are associated with the particulate matter present in vertical columns of the atmosphere. Therefore, to interpret the atmospheric pollution, it is expressed that this value varies between 0 and 1. AOD values approaching zero (0) indicate a low amount of aerosols, representing a clean atmosphere in terms of particles. On the other hand, AOD values approaching one (1) show a high amount of aerosols, meaning a layer of heavily polluted atmosphere.

AOD can be determined using specially established ground-based stations. For this purpose, 365 stations have been installed within the boundaries of our country. Initially, in 2005, only sulfur dioxide (SO_2) and PM10 particulate matter data were collected, but later on, data for ozone (O_3), carbon monoxide (CO), nitrogen dioxide (NO_2), and 2.5 μm particulate matter were also collected. The amount of pollutants is measured and recorded on an hourly and daily basis, and the data is shared. Through these stations, the levels of air pollution in different regions of Turkey can be monitored and tracked. National and international regulations have set specific limits for the quantity of pollutants in the air. Our legislation aims to achieve the air quality standards specified by the European Union. desired not to exceed the pollutant criteria set for 2019 and 2024 [34]. When these limits are exceeded, or the established threshold levels are reached, necessary measures and precautions are taken to reduce pollution [35].

AOD can be measured using ground-based data and satellite data in recent times [2]. In this study, the MODIS satellite was used, specifically the MCD19A2 V.6 data product. It has a resolution of 1 km and can collect data daily. At two different wavelengths, namely 470 nm (blue band) and 550 nm (green band), MCD19A2 supplies AOD data for the benefit of users. [19].

Among the available options, AOD at 550 nm (green band) from the V.6 product file was selected for the study because it displayed better consistency. [19, 36]. The product file contains information about water vapor (column) from the land surface, aerosol optical depth and type, AOD uncertainty, and smoke cloud height, as well as AOD outside of the glint area (glint angle $\geq 40^{o}$) and sensitive mode fraction data from the water surface [35]. Table 1 contains the specifics of the AOD product employed in the present study. Data for the months and the entire year of 2022 were obtained through coding on the GEE platform. This platform is free and open to everyone. Through the web-based application, analysis and visualization tasks can be completed quickly [6]. GEE libraries can be used to create programs in JavaScript and Python [37]. The data were downloaded for each station and the entire study area, and then exported. By examining the relationship between the stations, data processing, map preparation, and evaluation of the results were carried out using GIS software.

Table 1. Description of the AOD product utilized in the current research

Datasets	Period of time	Chosen band	Spatial resolution	Temporal resolution	Citation
MCD19A2 (Aerosol Optical Depth) V6	01.01.2022-31.12.2022	550 nm (green band)	1 km	Daily	[18]

3. RESULTS AND DISCUSSION

In the conducted study, AOD was determined using both ground-based stations and satellite images. The study's main objective was to obtain clear information about AOD for the region where fixed stations were installed while making interpretations for certain distance areas. However, AOD obtained from satellite images allows for spatially distributed results.

In the study's first stage, data was gathered from all stations in the national monitoring of air quality network located within the study area. (Table 2). Data for both particle sizes, 2.5 μm and 10 μm, were downloaded. It should be noted that data for particle size 2.5 μm is not available for Kardemir 1 and Kardemir 2 stations, and data for particle size 10 μm is not available for the 75.yıl station. The air pollution legislation sets different limits for PM10 to protect human health on an hourly, winter season (October to March), and annual basis. As of January 1, 2019, the daily national limit for particulate matter is 70 μg/m³, while the international limit is 50 μg/m³. The annual national limit is 48 μg/m³, and the international limit is 40 μg/m³ [19]. According to the obtained data, except for Kardemir 1 and Kardemir 2 stations, all other stations have not exceeded these legal limits. It should be noted that there is no specific standard for PM2.5 in the air quality index of our country.

Figure 3 presents the particulate matter data collected from the national air quality monitoring station for PM2.5, while Figure 4 illustrates the data for PM10. It can be observed that during the winter season, both PM2.5 and PM10 values are higher. This increase in values is attributed to an increase in the use of fuel for heating purposes and the activities of the iron and steel industry present in the region.

The data presented in Figure 3 reveals that the Safranbolu station experiences higher particulate matter levels in the times of July, August, and September. This can be attributed to Safranbolu being a popular tourist destination during the summer season, leading to an increase in the population and transportation activities in the region.

The higher levels of particulate matter during specific periods in both Safranbolu and the winter season indicate the influence of local activities and seasonal factors on air quality in the region. Monitoring and understanding these variations in particulate matter levels are crucial for implementing appropriate measures to mitigate air pollution and improve air quality in the area.

Table 2. Information from Air Quality Stations

Stations	Parameters	Unit	Minimum Value	Maximum Value	Average Value	Standard Deviation	Number of Data	Accessible Data Percentage
75. Yıl	PM 2.5	μg/m³	4,16	83,4	19,69	14,06	328	89,86
Kardemir 1	PM 2.5	μg/m³	-	-	-	-	0	0
Kardemir 2	PM 2.5	μg/m³	-	-	-	-	0	0
Safranbolu	PM 2.5	μg/m³	1,45	53,7	16,15	9,46	314	86,03
Tören Alanı	PM 2.5	μg/m³	0,93	84,54	14,75	12,12	363	99,45
75. Yıl	PM10	μg/m³	-	-	-	-	0	0
Kardemir 1	PM10	μg/m³	12,18	311,11	67,39	38,93	271	74,25
Kardemir 2	PM10	μg/m³	10,52	694,12	50,75	47,9	275	75,34
Safranbolu	PM10	μg/m³	2	161,02	43,5	19,68	349	95,62
Tören Alanı	PM10	μg/m³	8,67	136,63	47,31	22,58	357	97,81

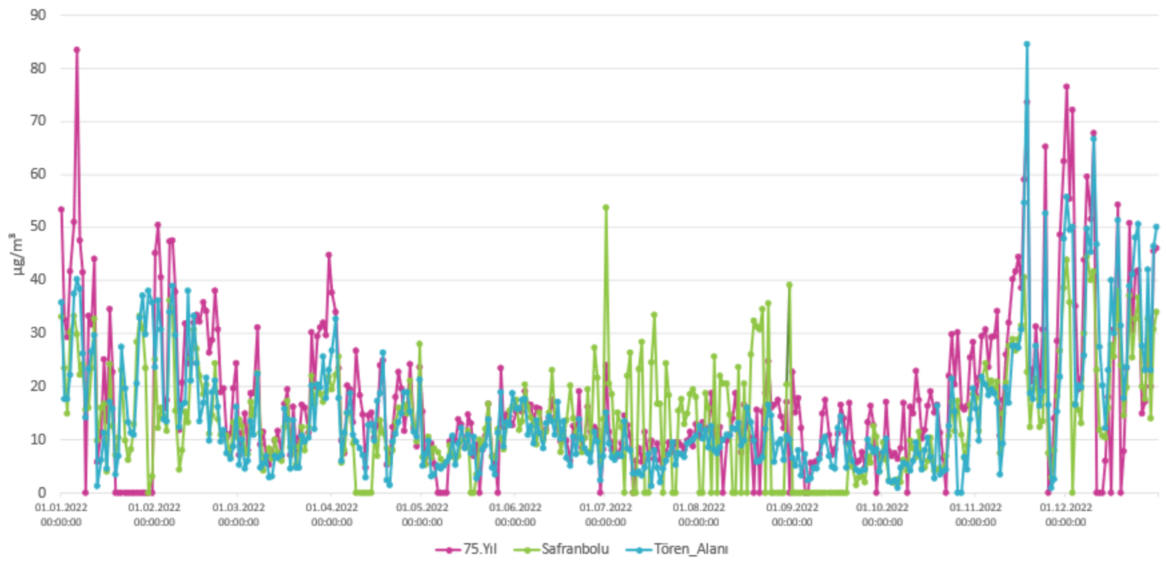

Figure 3. NAQMS Karabuk province PM2.5 values

The analysis of the PM10 graph also shows that particulate levels are higher during the winter season compared to the summer season (Figure 4). Among the four stations (Tören Alanı, Safranbolu, Kardemir 1, and Kardemir 2) that provide PM10 data, Kardemir 1 and Kardemir 2 stations have higher levels of particulate matter. These two stations are located close to iron and steel factories in the center of Karabük. Consequently, the higher values recorded in these two stations can be attributed to the active operations of these factories compared to the others.

Starting from October, both Kardemir 1 and Kardemir 2 stations have not recorded any data. Until October 2022, data sharing was possible for both stations. However, due to the change in servers, data access for this time period is currently unavailable. Initially, data sharing was done through the FTP system, but it has been transitioned to the VPN system. Since then, data for both stations is no longer publicly accessible but can be obtained upon official request. It is essential to consider the absence of data for the Kardemir 1 and Kardemir 2 stations when analyzing and interpreting the overall air quality trends in the region. The lack of data for these two stations during the specified period might influence the overall assessment of air quality for that time frame. Efforts should be made to address these data gaps and ensure a continuous and comprehensive monitoring system for air quality in the region.

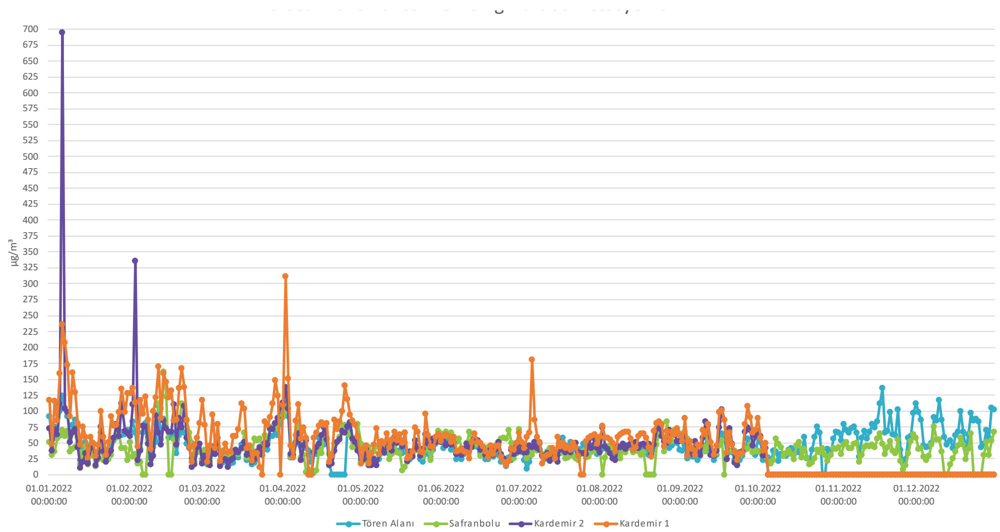

Figure 4. NAQMS Karabuk province PM10 values.

The majority of the monitoring stations established in our country are located in urban centers, resulting in limited coverage in rural areas. Additionally, some stations have missing data, and the point-based data collection method has its limitations. Due to these factors, satellite imagery has been utilized to complement and supplement the station data.

In the GEE platform, the locations of the stations were defined, and AOD data for the visible wavelength blue band and green band from the MODIS satellite were downloaded for each station. For each station, AOD over land graphs in the 0.47 μm band are shown in Figure 5, and AOD graphs in the 0.55 μm band are shown in Figure 6. Both bands provide four values for each day, resulting in some days having continuous data, while others have data gaps throughout the day. Furthermore, in some months such as January, February, and December, some data points are missing during the winter season, mainly due to climatic factors like snowfall. Snow particles can obscure particulate matter and lead to lower reflectance [22]. Generally, based on the data obtained from station points, higher AOD values are observed during the summer months.

To analyze the correlation between AOD values obtained from station points and satellite imagery, the Tören Alanı station was chosen due to its abundant data. As a result, a significant correlation was established between the two data sets. Therefore, monthly AOD maps for the entire study area were created using satellite imagery.

The utilization of satellite data in addition to station data allows for a broader spatial coverage and helps overcome the limitations associated with station locations and data gaps. The use of satellite derived AOD maps provides significant understanding of the air quality trends and changes across the study area. This comprehensive approach enhances the understanding of aerosol distribution and its impact on the region's air quality.

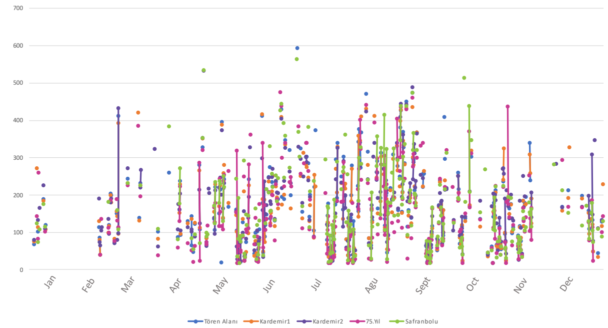

Figure 5. Blue band (0.47 μm) AOD over land

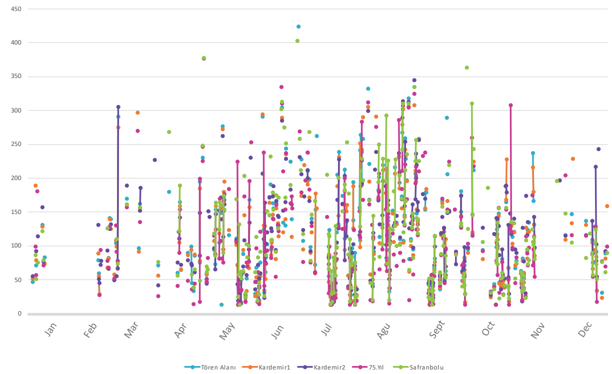

Figure 6. Green band (0.55 μm) AOD over land

The average AOD for the year 2022 and each month was calculated and analyzed using Google Earth Engine. The downloaded images were then mapped to create visual representations of the AOD values. Figure 7 shows the map of the average AOD for the year 2022, while Figure 8 presents the maps for each month of 2022. In the maps for February and March, some areas appear white, indicating that they do not have any AOD values. This is because during the winter season, snowfall can cover dust particles on the ground, resulting in a bright background in the satellite image. This variation in the reflective surface leads to the absence of AOD values in these regions [22]. Obtaining AOD values from satellite imagery during the winter season poses the biggest disadvantage due to this snow-cover issue. However, when calculating AOD for the entire region spatially rather than for individual stations, using satellite imagery becomes advantageous.

Overall, looking at all the monthly maps, it is evident that AOD values are higher in the city center. This is mainly attributed to the presence of iron and steel factories and private sector rolling mills in the city center. Additionally, higher population density in the urban areas and higher traffic circulation due to more motor vehicles contribute to this trend. As of 2022, there were 69,711 motor vehicles registered in Karabük, which means approximately one-third of the population (243,614) owns a vehicle [31]. The high number of vehicles generates exhaust pollution and releases multiple pollutants into the atmosphere. AOD levels are particularly high in areas with transportation networks. The months of July and August also show higher AOD levels compared to other periods. This trend is observed in the Safranbolu station as well, as previously mentioned. For other districts, especially Eskipazar and Yenice, AOD values are higher. Eskipazar attracts tourists due to the presence of an ancient city, while Yenice shows higher AOD levels until October.

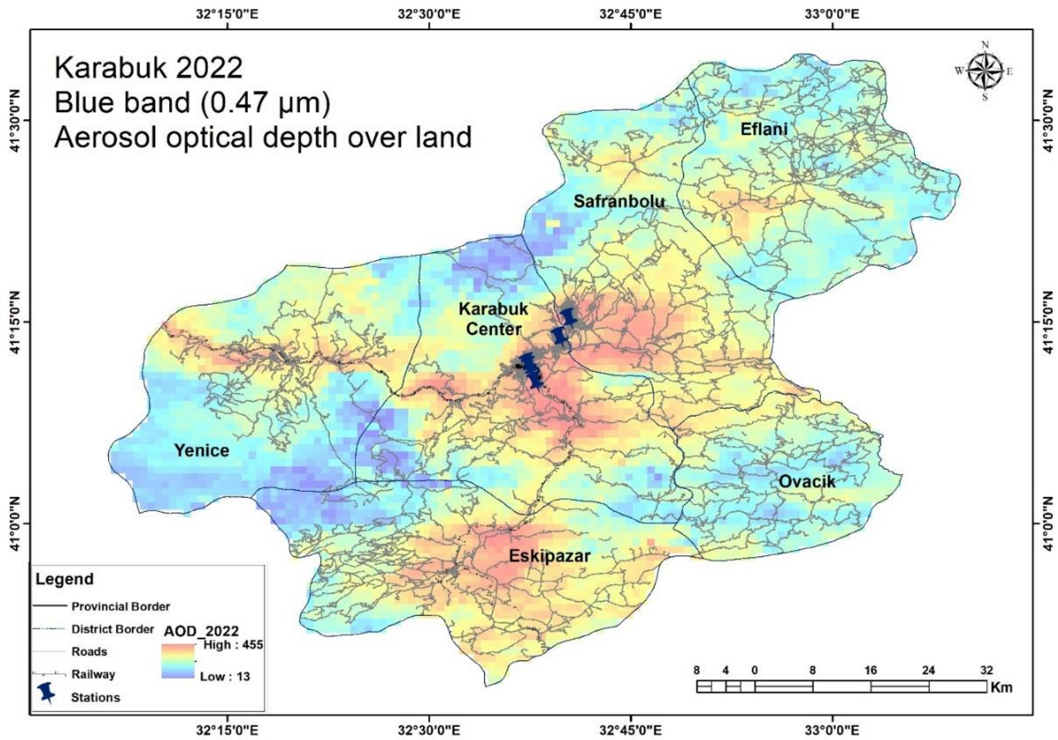

Figure 7. Blue band (0.47 μm) mean AOD over land map for 2022

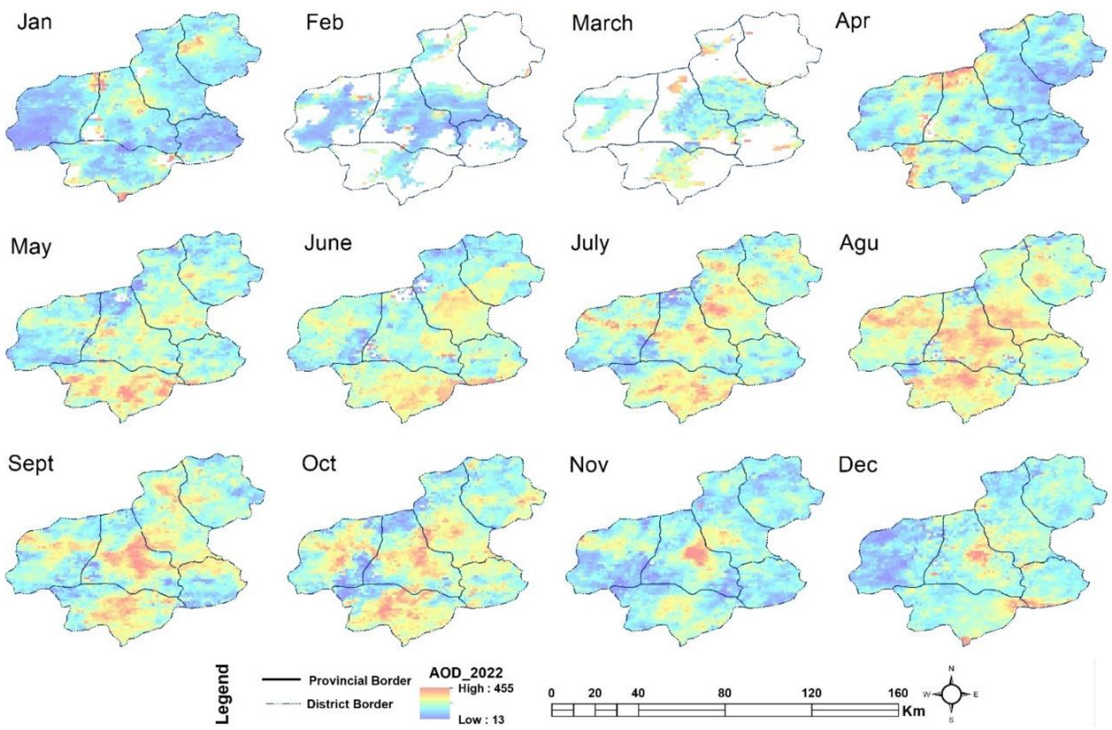

Figure 8. 2022 monthly AOD map

Figure 9 shows the graphs explaining the relationship between the two data by taking the average of the data from the satellite image and the terrestrial stations. In 'Figure 9a, the relationship between PM10 and PM2.5 is shown, while 'Figures 9b and 9c' depict the relationship between satellite imagery and ground-based data. There is a positive correlation of 85.24% among particulate matter obtained from ground stations. There is a 38.69% correlation between satellite imagery and PM2.5, and a correlation of

31.1811% between satellite imagery and PM10. Kaufman et al. (1997), Safarianzengir et al. (2020), and Makineci (2022) emphasized in their studies that the data obtained from Sentinel-5 and EOS Moderate Resolution Imaging Spectroradiometer are significant and positively correlated with the ground-based station data. In this study, it has been understood that, unlike other satellite systems, data from the MODIS satellite are consistent with ground-based data.

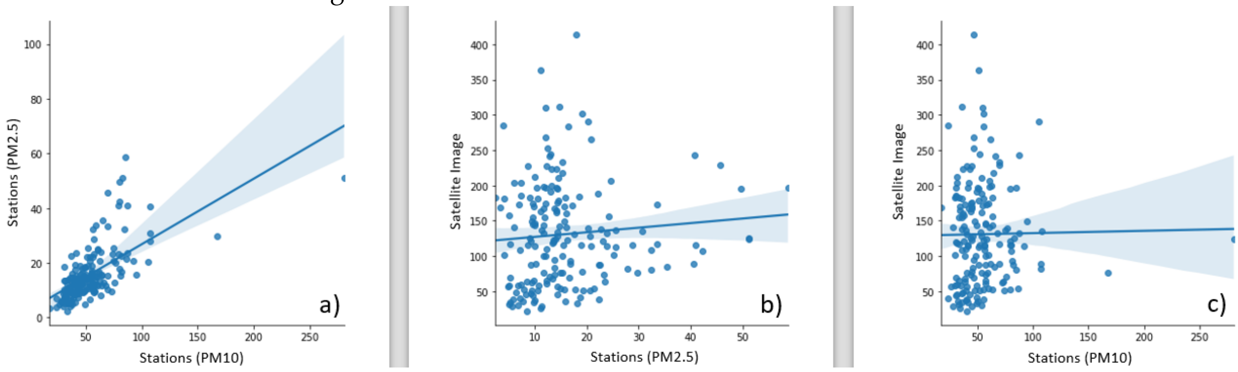

Figure 1. **a)** Relationship between PM10 and PM2.5, **b)** Relationship between satellite image and PM2.5, **c)** Relationship between satellite image and P10

4. CONCLUSIONS

In this study, the spatial-temporal variation of AOD derived from MODIS was monitored and investigated. The GEE platform was used in the implementation phase for satellite image acquisition, processing, and data analysis. A correlation was established between the AOD data derived from the ground based PM2.5 and PM10 measurements obtained from the Turkey National Air Quality Monitoring Stations and the satellite images. It was shown that there is a moderate link between the two, which is a substantial and positive association.

The presence and active operation of iron-steel factories and the high number of vehicles in the region cause to the increase in AOD levels. There is a direct proportionality between AOD and the amount of air pollution. When AOD levels are high, the pollution in the surrounding area also increases.

The AOD analysis investigated the monthly and annual changes within the year 2022. The results showed significant variations in AOD values among the four seasons (spring, summer, autumn, winter). During the summer season, anthropogenic activities led to higher AOD values compared to the winter season, with August showing the highest values.

According to the literature, it has been determined that humans may survive without food for five weeks, drink water for five days, and air for five minutes. However, humans need to receive a minimum of 15 μg/m3 of clean air daily. Pollutant gases are released into the atmosphere throughout the region, posing a significant impact on the quality of human life. Therefore, monitoring air pollution in the region and implementing measures to reduce pollutant levels are essential for safeguarding public health.

Thanks to this study, the AOD in Karabük, a region with a significant presence of the iron and steel industry, has been examined not only temporally but also spatially. This enhances the region's capacity to understand and monitor air quality. It proves to be a valuable tool for identifying sources of air pollution and developing air quality management strategies. Furthermore, it has been demonstrated that satellite imagery can be utilized when there is a lack of data at ground stations. Thus, satellite data can make a valuable contribution to filling data gaps in the air quality monitoring system.

In conclusion, this study represents significant research highlighting the potential of remote sensing and satellite data for monitoring air quality and filling data gaps. It also provides valuable insights for experts working in atmospheric sciences.

Declaration of Ethical Standards

Authors declare to comply with all ethical guidelines, including authorship, citation, data reporting, and original research publication.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding / Acknowledgements

This study was orally presented at the 12th National Photogrammetry and Remote Sensing Association Symposium (TUFUAB'XII).

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