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Determining the Factors Affecting Air Quality in Marmara, Turkey, and Assessing it Using Air Quality Indices

Ismet Yener[1], Kazım Onur Demirarslan[2,*]

[1] *Artvin Coruh University, Department of Forestry, 08000, Artvin.*
[2] *Artvin Coruh University, Department of Environmental Engineering, 08000, Artvin.*

Abstract

Air pollution due to anthropogenic activities is currently one of the most important problems faced worldwide. This study aimed to determine the associations between air quality and spatial, meteorological, and anthropogenic factors while evaluating air quality using the air stress index (ASI) and the daily air quality (DAQx) scale. The annual mean levels of CO, NO_x, O_3, PM 2.5, PM10 and SO_2 in the region were 718.6, 39.5, 44.4, 25.5, 51.3, and 9.9 µg/m^3, respectively. While anthropogenic variables mostly affected NO_x (r=0.56 to 0.64) and O_3 (r=-0.34 to 0.64), meteorological (r=-0.38 to 0.45) and spatial factors (r=-0.41 to -0.65) mostly affected particulate matter (PM2.5 and PM10). CO and SO_2, on the other hand, were affected by all types of variables at varying directions and rates. The mean ASI and DAQx values of 2.1 and 4.3 indicated that the air quality in the region exhibited distinct air stress and sufficient air quality, respectively. The findings and outcomes could contribute to understanding and evaluating the air quality in the region and could be used as a base for further studies.

Keywords
Correlation Analysis, Air Stress Index, Daily Air Quality Index, Air Pollution

Marmara Bölgesinde Hava Kalitesini Etkileyen Faktörlerin Belirlenmesi ve Hava Kalitesi Endeksleri Kullanılarak Değerlendirilmesi

Özet

Antropojenik faaliyetlere bağlı hava kirliliği dünya çapında karşılaşılan en önemli sorunlardan biridir. Bu çalışma, bir yandan hava stres indeksi (ASI) ve günlük hava kalitesi (DAQx) ölçeğini kullanarak hava kalitesini değerlendirirken diğer yandan hava kalitesi ile mekansal, meteorolojik ve antropojenik faktörler arasındaki ilişkileri belirlemeyi amaçlamıştır. Bölgedeki yıllık ortalama CO, NO_x, O_3, PM2.5, PM10 ve SO_2 seviyeleri sırasıyla 718.6, 39.5, 44.4, 25.5, 51.3 ve 9.9 µg/m^3'tür. Antropojenik değişkenlerin en çok NO_x (r=0,56 ila 0,64) ve O_3 (r=-0,34 ila 0,64) kirleticilerini etkilerken, meteorolojik (r=-0,38 ila 0,45) ve mekansal faktörler ise (r=-0,41 ila -0,65) en çok partiküler madde miktarını etkilemiştir. CO ve SO_2 ise her türlü değişkenden farklı oranlarda etkilenmiştir. ASI ve DAQx değerleri ortalama 2.1 ve 4.3 olarak bulunmuş ve bölgedeki hava kalitesinin sırasıyla belirgin hava stresi ve yeterli hava kalitesi sergilediğini göstermiştir. Bu çalışmanın bulgu ve sonuçları, bölgedeki hava kalitesinin daha iyi anlaşılıp değerlendirilmesine katkı sağlayabilir ve ileride yapılacak çalışmalar için bir temel oluşturabilir.

Anahtar Sözcükler
Korelasyon Analizi, Hava Stres Indeksi, Günlük Hava Kalitesi Indeksi, Hava Kirliliği

1. Introduction

Human activities affect air quality in a similar manner to other natural resources, such as soils, water, and forests. Their negative effect on air quality has increased as industrial, technological, and urban development have progressed. The emission of harmful suspended particulate matter (PM2.5 and PM10) and other gases, such as carbon monoxide, sulfur dioxide, nitrogen oxide, and ozone, emitted into the atmosphere from various sources has caused significant air pollution (Liu et al. 2018). Air pollutants can be classified as primary or secondary. Primary pollutants are directly released from their sources, while secondary pollutants occur due to a combination of two or more primary pollutants or because of typical atmospheric components. Primary pollutants include PM2.5, PM10, sulfur dioxide, nitric oxide, hydrocarbons, volatile organic compounds, carbon monoxides, and ammonia; while ground-level ozone is an example of a secondary pollutant (Tan 2014). The US Environmental Protection Agency (EPA 2007) defines air pollution as the presence of contaminants or pollutants that adversely affect human health and welfare, or cause other destructive environmental effects. Most countries are affected by air pollution and related diseases, and new respiratory diseases arise daily due to air pollution (Plaia and Ruggieri 2011).

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* Sorumlu Yazar: Tel: +90 (466) 2151040 Faks: +90 (466) 2151057
E-posta: yener@artvin.edu.tr (Yener İ), onurdemirarslan@artvin.edu.tr (Demirarslan K.O)

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Therefore, air pollution is considered a threat to the public and governments, as well as the environment. Seven million people die annually due to this issue, including 4.2 million premature deaths (Plaia and Ruggieri 2011; WHO 2020). Çapraz et al. (2016) observed a positive relationship between the increase in air pollution and mortality in Istanbul, with SO_2 being the pollutant with the greatest effect on mortality. Another study reported that exposure to ambient air pollutants, such as NO_2, PM10, and SO_2, causes reduced pregnancy and live birth rates from in vitro fertilization (Shi et al. 2021). Population growth has caused air pollution due to rapid and widespread industrial and urban development, increased motor vehicle abundance, and excessive fossil fuel use. The geographic positions of cities and meteorological elements also adversely affect air quality (Mamtimin and Meixner 2011). Air pollution in urban areas exhibits different characteristics due to changes in climatic factors based on their geographical and topographical features (Vieira-F et al. 2015).

Therefore, the availability of accurate and abundant data and their interpretation are vital in air quality management decisions. Similar to other countries, the limited number of air pollutant monitoring stations is a severe problem in many parts of Turkey. Therefore, relationships between environmental factors and air quality andestimation models have become critical as they provide a valuable estimation of air pollutants and quality in areas without measurement stations (Tikhe et al. 2017). Spatial modeling to predict and/or estimate air pollution based on measurements at sample points has become a common practice in recent decades, as such models can help policy-makers to understand the spatial distribution of air quality trends. Policy-makers must understand the sources of air pollution, how to determine its effects, and how to reduce its harmful effects on human health and ecosystems (Karroum et al. 2020).

Many researchers in Turkey and overseas have applied air quality prediction models using different factors, such as the climate and topography (Aggarwal and Toshniwal 2018; Altincop and Oktay 2018; Atamaleki et al. 2019; Buchholz et al. 2016; Çiftci et al. 2013; Cuhadaroglu and Demirci 1997; Gocheva-I et al. 2018; Gu et al. 2018; Hu et al. 2017; Jamal and Nodehi 2017; Karroum et al. 2020). Others have correlated the levels of air pollutants with population density, traffic, and the morphology of the settlement area (Caf et al. 2017; Han and Naeher 2006; Hu et al. 2017) by using various statistical methods and models, such as multilinear regression (MLR), regression trees (RTs), artificial neural networks (ANNs), random forest (RF), and land-use regression (LUR), which can provide advanced air pollution information at early stages; this allows the implementation of methods that can control air pollution and protect public health (Bai et al. 2016).

Large cities are most affected by air pollution due to increasing industrial and urban development. The Marmara Region of Turkey, comprising a megacity, Istanbul, along with a few large cities, such as Bursa, and Kocaeli, is one of the most air pollution-affected areas in the world. As the population of the Marmara region has increased, the problem of air pollution has been exacerbated, particularly due to the increasing consumption of fossil fuels and number of motor vehicles. The population in the region is 23,389,506, accounting for 28.94% of the total population of Turkey (80,810,525). Furthermore, 48% of the industrial areas in the country are located in this region (Demirarslan and Akıncı 2018). Few studies modeled or evaluated the air quality throughout the whole region (Arslan and Akyürek 2018; Kasparoglu et al. 2018; Mentese 2019; Sarisaltik 2019), despite its economic and demographic importance and high level of air pollution. For example, Arslan and Akyürek (2018) spatially modeled the levels of PM10 and SO_2 by following standard ordinary least squares and spatially autoregressive regression techniques using meteorological variables, such as temperature, wind speed, humidity, and pressure. Therefore, the air pollution issue in this region, which is regarded as the heart of Turkey in terms of industrial, economic, and human resources, must be resolved.

The objective of the present study is to (i) determine the relationships between air quality in the Marmara Region and climatic, topographic, and anthropogenic variables and (ii) assess the air quality in the region using the air stress index (ASI) and daily air quality (DAQx).

2. Materials and Methods

2.1. Study Area

The study area is the Marmara Region of Turkey, located at 39°03′41″– 42°06′17″ N, 25°40′07″– 31°0′39″ E, covering an area of 152,771 km^2 (Figure 1). The region includes the cities of Balıkesir, Bilecik, Bursa, Çanakkale, Edirne, Istanbul, Kırklareli, Kocaeli, Sakarya, Tekirdağ, and Yalova. The elevation of the area ranges between 0 and 2534 m asl. According to the Köppen-Geiger classification, the region experiences a dry summer subtropical Mediterranean climate or a temperate rainy climate with dry summers (humid mesothermal; i.e., Cs (mostly Csa)). Seasonal soil moisture deficiency is evident, particularly during the summer (Turkes 2020).

The average temperature ranges from 3.9 °C in the winter to 26 °C in the summer, with an annual mean of 14-16 °C. The annual mean precipitation ranges from 600 to 700 mm and is mainly concentrated in the winter. The average relative humidity (RH) is approximately 73% (Kasparoglu et al. 2018; Sensoy et al. 2008).

2.2. Data and Methodology

Air quality, air pollutant, and meteorological data were gathered from 70 air quality monitoring stations of the following types: heating (37.1%), air quality (25.7%), urban-traffic (10.0%), rural (10.0%), urban-industrial (8.6%), and no information (8.6%), and 180 weather stations distributed across the Marmara Region (Figure 1). Each air quality and pollutant monitoring station also observed weather data. Therefore, weather data were obtained from 250 stations in total. However, PM10 (particulate matter with diameter < 10 μm), NO_x (nitrogen oxides), SO_2 (sulfur dioxide), O_3 (ground-level ozone), CO (carbon monoxide), and PM2.5 (particulate matter with diameter<2.5 μm) data were available from 58, 58, 55, 37, 27, and 19 stations, respectively. Air quality data from January 1 to December 31, 2017 (one year), were obtained from 70 air quality stations monitored by the Turkish Ministry of Environment and Urbanization (URL-1 2018). PM2.5 and PM10, SO_2, O_3, CO, and NO_x levels were measured using beta-attenuation control, UV fluorescence, UV photometry, non-dispersive infrared photometry, and gas-phase chemiluminescence according to the EPA, respectively (Gilliam and Hall 2016). Meteorological data, including the temperature (Temp), precipitation (Prec), relative humidity (RH), air pressure (Pres), wind speed (WS), and wind direction (WD), were obtained from the Turkish State Meteorological Service (TSMS 2017).

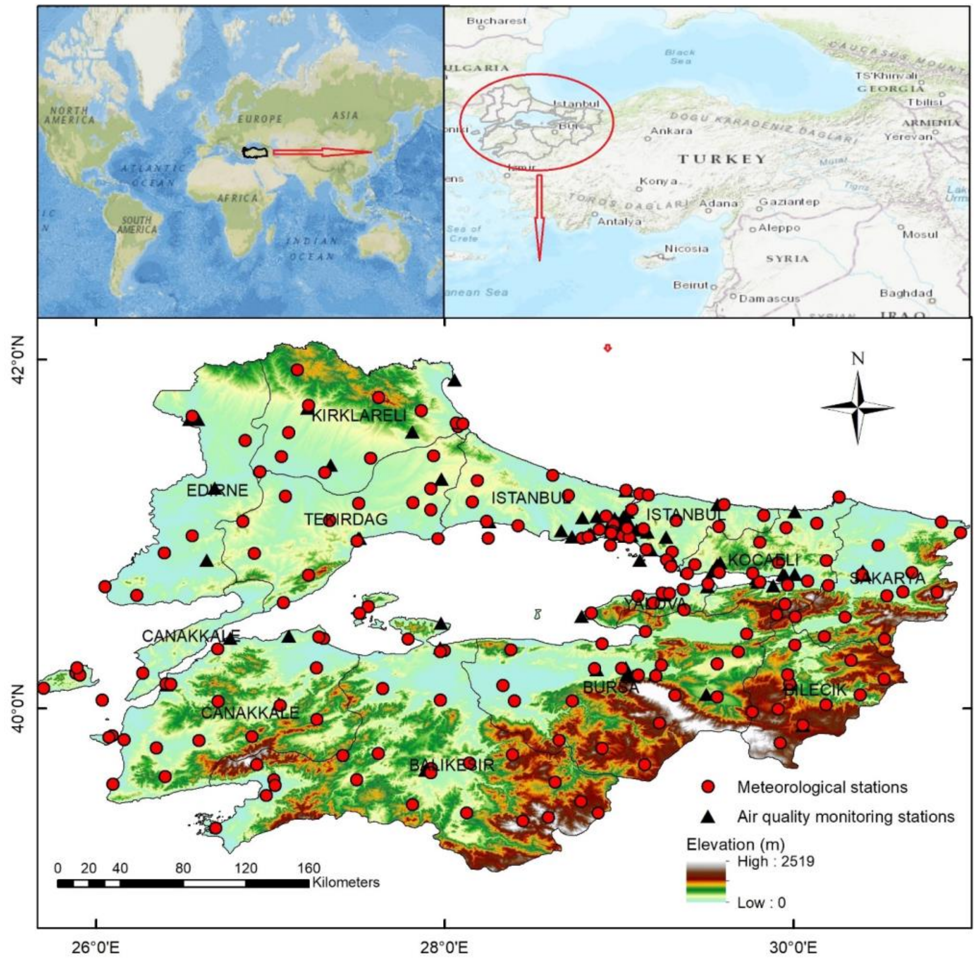

Figure 1: Air quality monitoring and meteorological stations used for the present study

Missing pollutant (12 for PM10, 12 for NO_x, 15 for SO_2, 33 for O_3, 43 for CO, and 51 for PM2.5), meteorology, and traffic data points were extracted from maps prepared in the ARCMAP 10.2 software by following inverse distance weighted (IDW) methods using the "extract values to points" tool (Childs 2004; ESRI 2014).

Seasonal variations in meteorological variables may partly cause seasonality in air pollution (Li et al. 2014). Therefore, in this study, air pollution affected by meteorological and other variables was assessed by seasons, including spring (1), summer (2), autumn (3), and winter (4).

The latitude (Lat), longitude (Long), and elevation (Elev) data of the monitoring stations were also collected. In addition to spatial and meteorological data, anthropogenic data, such as the number of vehicles and population of the county and district, were also used as independent variables. The number of vehicles was obtained from a map (URL-2 2018) by digitizing and interpolating the data for monitoring station locations and human populations (URL-3 2017).

Many indices, including the air quality index (AQI), such as the common, oak ridge, new, and pollution AQIs, air quality depreciation index, and air stress index, have been developed and their usage varies between countries (Mandal and Gorai 2014; Plaia and Ruggieri 2011). AQI is a ranking index based on the total of air pollutants, which is used to protect human health, as it also indicates how air quality affects human health and the environment.

The AQI was examined and classified into the following six categories: good (0-50), moderate (51-100), unhealthy for sensitive groups (101-150), unhealthy (151-200), very unhealthy (201-300), and hazardous (301-500) (EPA 2014). These indices have been used for many purposes, including the assessment of the results of air pollution interventions, monitoring pollution trends, and providing pollution level data to people. The ASI, one of two indices used in this study, was developed for providing continuous population-related air quality information (Mayer et al. 2004), and was formulated and scaled as described below (Equation 1, Table 1). The DAQx, an impact-related index valid for providing information to people on the Internet, was calculated for each pollutant according to Table 2 and is represented by six classes (Table 2) formed by assigning ambient air pollutants to different pollutant ranges (Equation 2).

$$ASI_{Bw} = \frac{C(SO_2)}{350\mu g} + \frac{C(CO)}{10000\mu g} + \frac{C(NO_2)}{200\mu g} + \frac{C(O_3)}{180\mu g} + \frac{C(PM10)}{50\mu g} \tag{1}$$

where $C(SO_2)$, $C(NO_2)$, and $C(O_3)$ are the specific highest daily 1-h mean concentrations, while C(CO) is the highest daily running 8-h mean concentration and C(PM10) is the daily mean concentration. The ASI was scaled as shown in Table 1.

$$DAQx = \left[\left(\frac{DAQx_{up} - DAQx_{low}}{C_{up} - C_{low}}\right) * (C_{inst} - C_{low})\right] + DAQx_{low} \tag{2}$$

where C_{inst} shows the highest daily 1-h concentration of SO_2, NO_2, and O_3, highest daily running 8-h mean concentration of CO, and mean daily concentration of PM10; C_{up} and C_{low} are the upper and lower thresholds of specific air pollutant concentrations, respectively; and $DAQx_{up}$ and $DAQx_{low}$ are the index values based on C_{up} and C_{low}, respectively (Table 2).

Table 1: Air quality categories corresponding to ASI ranges (Mayer et al. 2004)

Pollution category	ASI ranges	Description
1	ASI < 0.5	Very low air stress
2	0.5 ≤ ASI < 1.1	Low air stress
3	1.1 ≤ ASI < 1.7	Moderate air stress
4	1.7 ≤ ASI < 2.3	Distinct air stress
5	2.3 ≤ ASI < 2.9	Strong air stress
6	ASI ≥ 2.9	Extreme air stress

Table 2: Assignment of ranges of specific air pollutant concentrations to DAQx values and DAQx classes(Makra et al. 2003)

NO_2 (µg/m^3)	SO_2 (µg/m^3)	CO (mg/m^3)	O_3 (µg/m^3)	PM10 (µg/m^3)	DAQx value	DAQ class	Classification
0–24	0–24	0.0–0.9	0–32	0.0–9.9	≤1.4	1.0	very good
25–49	25–49	1.0–1.9	33–64	10.0–19.9	1.5–2.4	2.0	good
50–99	50–119	2.0–3.9	65–119	20.0–34.9	2.5–3.4	3.0	satisfying
100–199	120–349	4.0–9.9	120–179	35.0–49.9	3.5–4.4	4.0	sufficient
200–499	350–999	10.0–29.9	180–239	50.0–99.9	4.5–5.4	5.0	poor
≥500	≥1000	≥30	≥240	≥100	≥5.5	6.0	very poor

2.3. Statistical Analyses

Spearman's correlation coefficient was calculated to examine the relationships between air pollutants and other factors, followed by determining descriptive statistics using R (Team 2013). Because of the non-normal distributed data, Dunn's Bonferroni test for pairwise comparisons after the Kruskal Wallis test, the non-parametric equal of one-way ANOVA, was used to determine significant differences by seasons.

3. Results and Discussion

The CO concentrations in the spring, summer, autumn, and winter in the Marmara region were 624.2, 485.5, 687.4, and 727.5 µg/m^3, respectively, and the annual concentration was 654.9 µg/m^3. The summer CO level was significantly lower than that of the others, according to the Kruskal-Wallis test (Table 3). The NO_x concentrations in the spring, summer, autumn, and winter were 38.8, 26.4, 38.6, and 41.0 µg/m^3, respectively, and the annual concentration was 37.8 µg/m^3. The summer NO_x level was significantly lower than those of the other seasons, according to the Kruskal Wallis test (Table 3). The O_3 concentrations were 51.4, 62.6, 35.9, and 33.5 µg/m^3 in the spring, summer, autumn, and winder, respectively, with an annual average of 43.5 µg/m^3. The spring and summer O_3 levels were significantly higher than those in the autumn and winter, according to the Kruskal-Wallis test (Table 2). The PM2.5 concentrations in the spring, summer, autumn, and winter were 26.0, 20.7, 25.3, and 27.8 µg/m^3, respectively, with an annual mean of 25.1 µg/m^3. The PM2.5 level significantly increased in the following order, according to the Kruskal-Wallis test: summer<autumn<<spring<<winter. The PM10 concentrations in the spring, summer, autumn, and winter were 50.1, 42.9, 55.1, and 45.7 µg/m^3, respectively, and the average annual concentration was 49.2 µg/m^3. The summer PM10 level was significantly lower than that of the other seasons, according to the Kruskal-Wallis test (Table 3). The SO_2 concentrations were 8.8, 4.8, 7.4, and 9.9 µg/m^3 in the spring, summer, autumn, and winter, respectively, and the average annual concentration was 8.2 µg/m^3. The SO_2 level significantly increased in the following order, according to the Kruskal-Wallis test: summer<autumn<<spring<<winter. Except for the O_3, all pollutants' levels in the summer were lower than in other seasons. The significantly lower pollutant levels in summer could be attributed to the increasing temperature that causes low consumption of fossil fuels in households and reduced population and traffic as people spend their summer holidays outside the region. Similar results were found by Filonchyk and Yan (2018). They attributed the elevated level of PM2.5 and gas emissions in winter to coal and biomass combustion in residential areas, besides less precipitation and lower temperature. The factors causing higher air pollution (PM2.5) in the winter season were reported by Cheng et al. (2019) and Ngoc et al. (2021) as human activities such as coal, oil consumption, and vehicle emissions and boundary layer in winter.

Table 3: Some descriptive statistics for air pollutants according to seasons

Season		CO (µg/m^3)	NO_x (µg/m^3)	O_3 (µg/m^3)	PM2.5 (µg /m^3)	PM10 (µg/m^3)	SO_2 (µg /m^3)
Spring	$\bar{x}$±SE	751.4±63.2	42.7±3.2	50.1±2.5	26.6±0.5	53.4±2.4	10.6±0.8
	M	624.2^a	38.8^{ab}	51.4^a	26.0^{bc}	50.1^b	8.8^{bc}
	Min	52.4	4.3	6.7	17.5	10.8	2.2
	Max	3318.9	117.5	111.6	45.5	118.3	41.5
Summer	$\bar{x}$±SE	549±37.8	31.6±2.4	56.4±2.5	20.8±0.5	43.1±1.6	6.4±0.8
	M	485.5^b	26.4^a	62.6^a	20.7^a	42.9^a	4.8^a
	Min	37.7	1.5	5.6	14.6	9.6	1.6
	Max	1970.6	102.8	96.4	37.0	77.3	43.1
Autumn	$\bar{x}$±SE	740.8±45.1	41.7±2.7	37.2±1.7	26.2±0.5	59±2.9	8.8±0.8
	M	687.4^a	38.6^b	35.9^b	25.3^b	55.1^b	7.4^b
	Min	53.8	3.0	3.3	19.5	13.3	1.9
	Max	1984.9	89.9	76.7	41.9	122.1	43.1
Winter	$\bar{x}$±SE	835.4±52.1	41.8±2.6	33.7±1.5	28.5±0.6	49.8±2.6	13.7±1.3
	M	727.5^a	41.0^b	33.5^b	27.8^c	45.7^{ab}	9.9^c
	Min	18.1	5.1	8.2	18.8	16.0	2.0
	Max	1811.6	102.3	65.8	41.5	107.5	66.1
Annual	$\bar{x}$±SE	718.6±46.3	39.5±2.6	44.4±1.9	25.5±0.4	51.3±2.2	9.9±0.7
	M	654.9	37.8	43.5	25.1	49.2	8.2
	Min	40.5	4.1	6	19	12.5	2.1
	Max	2181.8	91.8	79.1	39.3	102.7	36.3

- *$\bar{x}$±SE: Mean±standard error, M: Median, Min:Min value, Max: Maximum value*
- *Lower-case letters indicate significant difference by season according to dune bonferroni test following Kruskal Wallis.*

3.1. Effects of Spatial, Meteorological, and Anthropogenic Factors on Air Pollutants

3.1.1. Spatial Factors

Spatial factors (variables), such as Lat and Long, significantly affected the air pollutant levels in varying directions and rates (Figure 2A-2E). Lat was positively correlated with PM2.5 (r = 0.31 to 0.40) and negatively correlated with O_3 (r = -0.25 to -0.28) and PM10 (r = -0.29 to -0.40), while Long was positively correlated with NO_x (r = 0.25 to 0.32) and SO_2 (r = 0.26) and negatively correlated with O_3 (r = -0.27) and PM2.5 (r = -0.62). Elev did not significantly affect the air pollutant levels.

The negative correlation between Lat/Long and particulate matter could be attributed to the cleansing effect of precipitation and increasing WS (r = 0.25 to 0.28). With increases in both Lat and Long, Prec increased significantly (r = 0.37 to 0.98). The increases in both NO_x and SO_2 with increasing Long could be attributed to urbanization and industrialization. The industrialization rate increased from west to east across the region, with higher rates in Istanbul (65%), Bursa (17%), and Kocaeli, located in the east, than those in Edirne (1%), Çanakkale (1%), and Kırklareli (1%), located in the west (PISR 2018). The increasing NO_x with increasing Long could also be due to the heavy traffic in cities, such as Istanbul, Bursa, and Kocaeli (r = 0.44 between Long and the number of motor vehicles (Vhcl)).

3.1.2. Anthropogenic Factors

Anthropogenic variables, such as the district population (Popdist), county population (Popcou), and Vhcl had significant positive or negative effects on air pollutants. All anthropogenic variables affected the same variable in the same direction, but at varying rates. The correlation coefficients between the NO_x and Popdist, Popcou, and Vhcl were r = 0.36 to 0.50, r = 0.49 to 0.60, and r = 0.57 to 0.61, respectively. Atmospheric NO_2 typically originates from two sources, both directly and indirectly involving chemical reactions (Han and Naeher 2006). Sharma (2007) reported that 8% of NO_x originates from automobile exhausts, while Sayegh et al. (2016) reported rates of 40.5% and 32% for European Economic Area countries and the United Kingdom, respectively.

The levels of O_3 and SO_2 were negatively correlated with Popdist, Popcou, and Vhcl, with r = -0.24 to -0.32 and -0.28, -0.40 to -0.57, and -0.27 to -0.35, and -0.36 to -0.55 and -0.29, respectively. The negative impact of anthropogenic factors on O_3 could be attributed to the increasing NO_2 due to increases in motor vehicle use, industrial activities, and population (r = -0.60 to -0.70 for O_3 and NO_2 in this study, respectively). Industrial processes and motor vehicle exhaust are two primary anthropogenic air pollution sources, in addition to solvents, food production, waste disposal, agriculture, oil refining, petrol storage and distribution, and gasoline vapors from motor vehicles (Chen et al. 2020). Ozone is classified as stratospheric (natural) or tropospheric (anthropogenic). The latter is formed in the troposphere when molecular O_2 reacts with O (3P) that primarily originates from the photodissociation of NO_2 at 280 to 430 nm. The O_3 formed in this manner reacts with NO to regenerate NO_2 (Godish and Fu 2003). Han et al. (2011) reported an inverse relationship between O_3, NO, and NO_2, which they attributed to the increasing solar radiation during the day (08.00 to 15.00) and height of the mixing layer, causing a reduction in NO_x and an increase in O_3. Han and Naeher (2006) and WHO (2020) reported that traffic (transport) emissions account for 12 to 70% of PM, 71.5% of NO_x, and up to 70% of CO of the air pollutants released to the atmosphere. The decreasing effects of anthropogenic factors on SO_2 may be attributed to the increasing use of natural gas instead of coal in the most populated and industrialized provinces of the region, such as Istanbul and Kocaeli. Caf et al. (2017) recorded an increase in the SO_2 and PM10 concentrations with increases in the numbers of cars and homes, and population, which was not the case in this study. The levels of PM2.5 and PM10 were only positively correlated with Popcou, with correlation coefficients of r = 0.26 and 0.28 to 0.37, respectively. Many researchers (Cramer 1998; Ghaedrahmati and Alian 2019; Han et al. 2018; Sarkodie et al. 2019) have studied the effects of population size on air pollution. For example, Cramer (1998) reported a positive correlation between the population size and NO_x ($R^2 = 0.52$), SO_2 ($R^2 = 0.74$ to 0.79), and PM10 ($R^2 = 0.30$ to 0.42). Sarkodie, Strezov (2019) and Han et al. (2018) also reported a positive correlation between the population size and PM2.5 (r = 0.72 to 0.79 and R^2 = 0.86 to 0.91, respectively) worldwide. Unal et al. (2011) reported higher PM10 concentrations, exceeding EU standards, in areas with high traffic and industrialization. The traffic volume, along with the wind and RH, temperature, precipitation, and snow cover, accounted for approximately 58%, 60%, and 68% of the variations in PM2.5, PM10, and NO_x, respectively (Aldrin and Haff 2005).

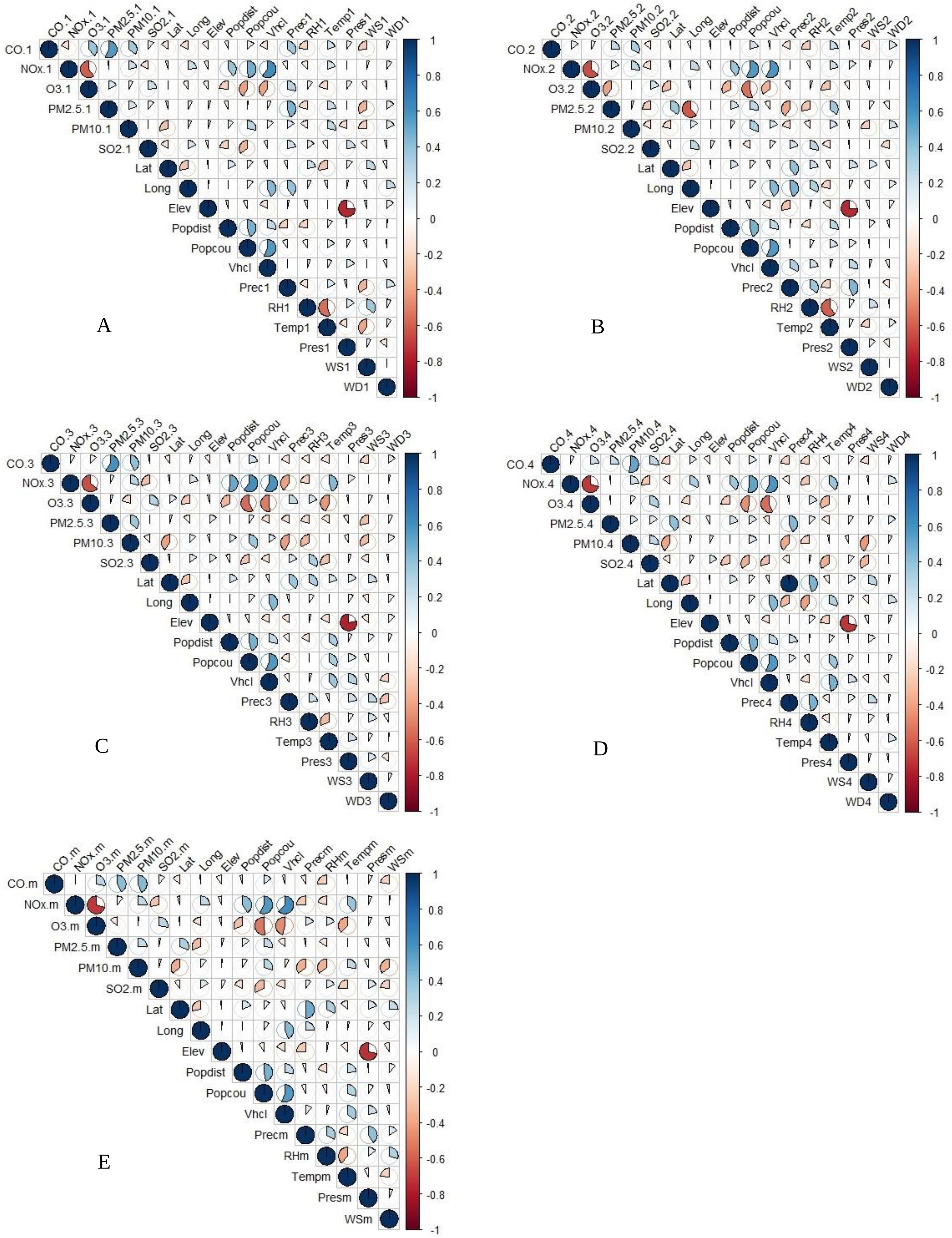

Figure 2: Spierman correlations between air pollutants and the other variables (A: Spring, B: Summer, C: Autumn, D: Winter and E: Annual)

3.1.3. Meteorological Factors

The meteorological variables, excluding WD, exerted significant positive or negative effects on air pollutants at varying rates (Figure 2A–2E). While Prec positively affected the levels of CO (r = 0.35) and O_3 (r = 0.25 to 0.28), it negatively affected the levels of NO_x (r = -0.40), PM2.5 (r = -0.40), and PM10 (r = -0.35).

However, RH was negatively correlated with the levels of CO (r = -0.25), NO (r = -0.26) and PM2.5 (r = -0.29), and positively correlated with the level of SO_2 (r = 0.28 to 0.32). The decreasing effect of Prec and RH on CO, NO_x, PM2.5, and PM10 could be due to the removal effect of rainfall and RH. Precipitation, which occurs when the RH reaches 100%, is one of the primary meteorological elements that cleanses the atmosphere (Holzworth 1974; Lei et al. 2019; Luo et al. 2017) through two routes, i.e., rainout (snow out) and washout, which refer to the capture of pollutants within clouds and below clouds, respectively, and result in lowered pollutant gas and aerosol concentrations (Holzworth 1974). Huo et al. (2011) also reported a similar result, with negative relationships between rainfall and the levels of NO_2 and SO_2. The increasing O_3 levels with precipitation could be attributed to the vertical mixing of the stratospheric and tropospheric O_3 during convective rain activity and thunderstorms (Martin 1984). Yoo et al. (2014) reported significant scavenging effects of rainfall on air pollutants, which decreased in the following order: PM10>SO_2>NO_2>CO>O_3. Huo et al. (2011) attributed this ordering to that CO and O_3 are less soluble than the other pollutants. The decreasing PM level with increasing RH could also be attributed to the increasing dry deposition with RH (Chen et al. 2012). Some researchers (Zannetti et al. 1977; Tong et al. 2018) reported a significant increasing effect of RH on SO_2, while others (Cuhadaroglu and Demirci 1997) reported a significant decreasing effect.

The temperature significantly affected the levels of NO_x (r = 0.37 to 0.43), PM2.5 (r = 0.37), PM10 (r = 0.26), O_3 (r = -0.26 to -0.44), and SO_2 (r = -0.29 to -0.35), with increasing temperatures corresponding to increasing PM and NO_x, levels, which may be due to the increasing number of vehicles, thereby increasing pollutant emissions (r = 0.37 to 0.46 between Temp and Vhcl). The NO_x level was almost proportional to the number of vehicles. Khedairia and Khadir (2012) also reported a positive relationship between Temp and PM10, and attributed this relationship to the more favorable atmospheric dispersion states that occur under high temperatures. The decreases in the SO_2 levels during autumn and winter with increasing Temp could be due to the lower use of fuels, especially coal, on warmer days during the colder seasons. Other researchers (Masoudi et al. 2018; Sarisaltik 2019; Zannetti et al. 1977) reported similar results. Sayegh et al. (2016) attributed this relationship to air masses moving upward with increasing temperature near the surface, causing air pollutants to rise and diffuse.

Increases in WS decreased the concentrations of CO (r = -0.24 to -0.26), PM2.5 (r = -0.29 to -0.35), PM10 (r = -0.24 to -0.43), and SO_2 (r = -0.35). Accelerating WS tends to increase friction velocity, dispersion, and dilution, favoring pollutant transport (Chen et al. 2012; Sarisaltik 2019). The average WS (1.5 m/s or less) and formation of inversion layers were correlated, particularly during cold seasons. The lower the WS, the more likely the formation of an inversion layer. Therefore, the WS should exceed 1.5 m/s to transport air pollutants (Holzworth 1974). Although many researchers (Agac 2016; Aggarwal and Toshniwal 2018; Bai et al. 2016; Luo et al. 2017; Masoudi and Gerami 2017; Zannetti et al. 1977) found WS to be negatively correlated with air pollutant levels (similar results), others (Chen et al. 2012; Haagenson 1979) have reported different results. For example, Luo et al. (2017) reported a decreasing effect on CO (r = -0.54) and PM2.5 (r = -0.39).

Owing to the correlation between meteorological factors and air pollutants, global climate change is expected to affect air pollution. In Turkey, an increase in temperature between 3 and 6 °C, particularly during the summer period, an increase in winter precipitation in most of the country, and decreases in precipitation during spring, summer, and autumn throughout the country, excluding coastal areas and the northeastern region, are expected (Demircan et al. 2014). Increases in temperature improve the bio-based emissions and chemical reactions, which promote the pollutant concentrations. Additionally, the decreased precipitation in most of the country will enhance the levels of pollutants, particularly ozone, due to the reduced removal by precipitation and increased photochemistry resulting from reduced cloudiness (Giorgi and Meleux 2007). Therefore, global climate change is one of the most significant determinants in air pollution estimations.

3.1.4. Assessment of Air Quality Using AQIs

One of the essential requirements for human health and well-being is clean air, which has been deteriorated by various human activities that have resulted in air pollution. Therefore, most countries measure, record, and monitor the levels air pollutants. However, the assessment and reporting of such complex data are difficult. Air quality indices have been developed and used, which are simple and rational approaches to evaluating air quality, along with its effects on both human and environmental health, and report it, monitor its trends, and develop reduction strategies (Plaia and Ruggieri 2011). In this study, we used the ASI and DAQx to evaluate air pollution in the Marmara Region, Turkey. The ASI and DAQx values calculated and interpolated for the Marmara Region are shown in Figures 4 and 5, and are compared by province in Figure 3. The ASI and DAQx indicated that the air quality in the region exhibited distinct air stress (mean value of 2.1) or was sufficient air quality (mean value = 4.3), respectively. The lowest and highest ASI and DAQx values were observed in the provinces of Çanakkale and Bursa, respectively, with Sakarya and Tekirdağ following Bursa for ASI and Sakarya and Balıkesir following Bursa for DAQx. The high pollution levels in Bursa, Sakarya, and Tekirdağ could be attributed to the high emissions from industrialization, urbanization, population density, and traffic. The lowest values were observed in the provinces of Çanakkale, Yalova, and Kırklareli, which could be attributed to lower population density and industrialization, higher number of agricultural areas, and lower level of traffic than the more industrialized provinces. The contribution of the pollutants to ASI increased in the following order: SO_2 (4.5%)<CO (5.8)<NO_x (16.5%)<O_3 (21.2) < PM10 (52.0%). The only contributor in DAQx, excluding O_3 and NO_x at five and three stations, respectively, was PM10.

Mayer et al. (2004) also used ASI and DAQx to assess the air quality in southwestern Germany and southern Hungary, and the ASI and DAQx values ranged from 0.86 to 1.32 and 3.02 to 3.19, respectively. Although PM10 and NO_2 were dominant in the ASI in southwestern Germany, PM10 and CO were dominant in the DAQx. Dimitriou and Kassomenos (2017) also reported that PM10 was the dominant pollutant in the ASI in southern Germany, followed by O_3. Makra et al. (2003) found that PM10 and CO were dominant for both ASI and DAQx.

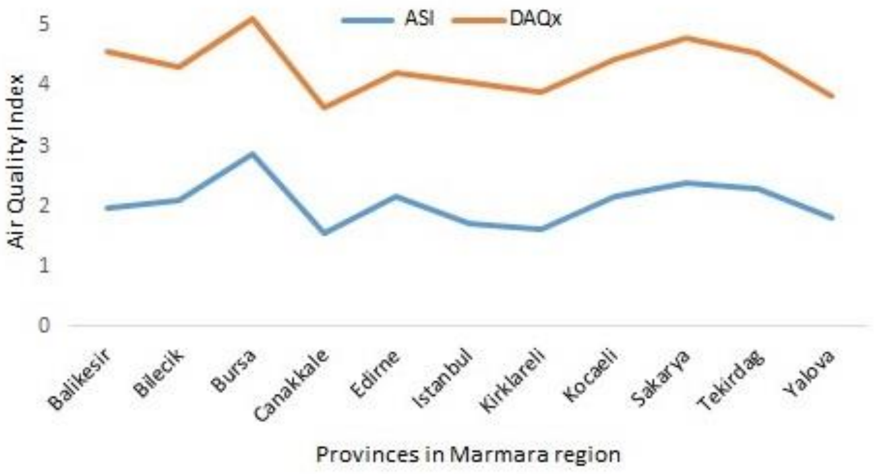

Figure 3: Annual mean ASI and DAQx values at Marmara region

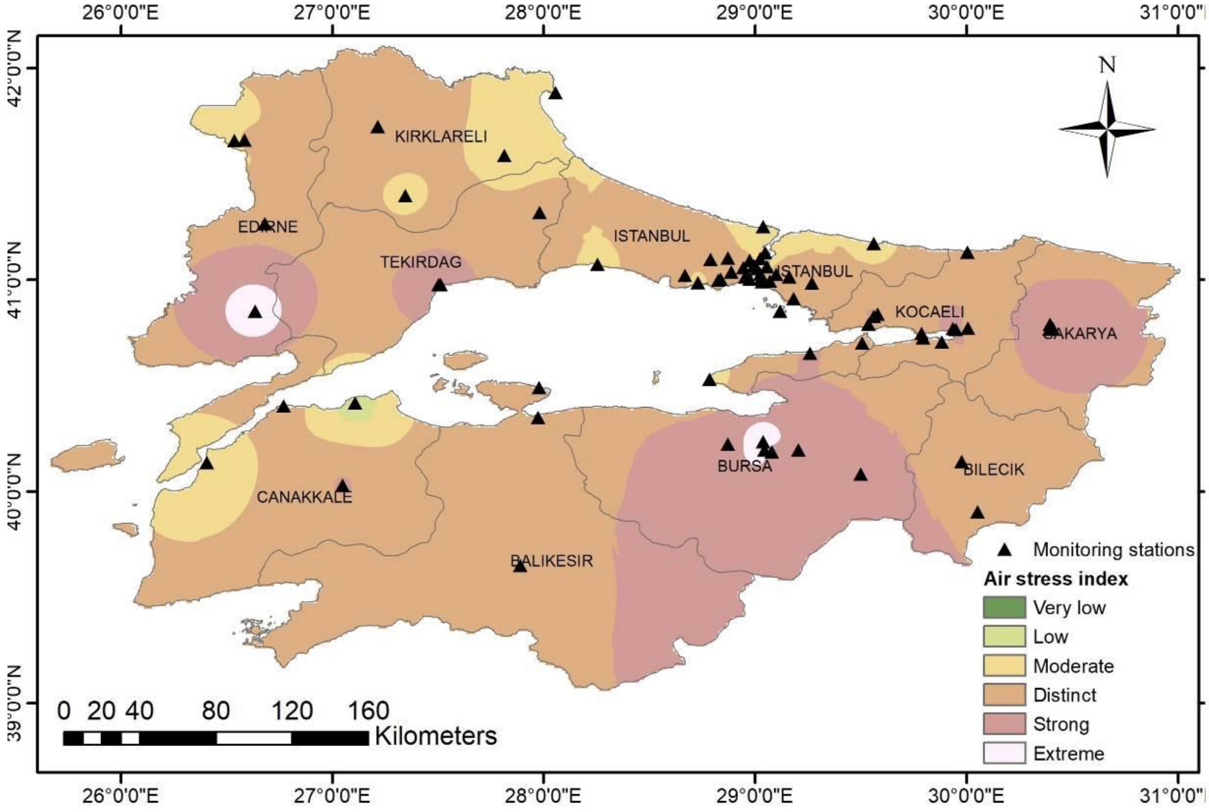

Figure 4: Air stress index map of Marmara region

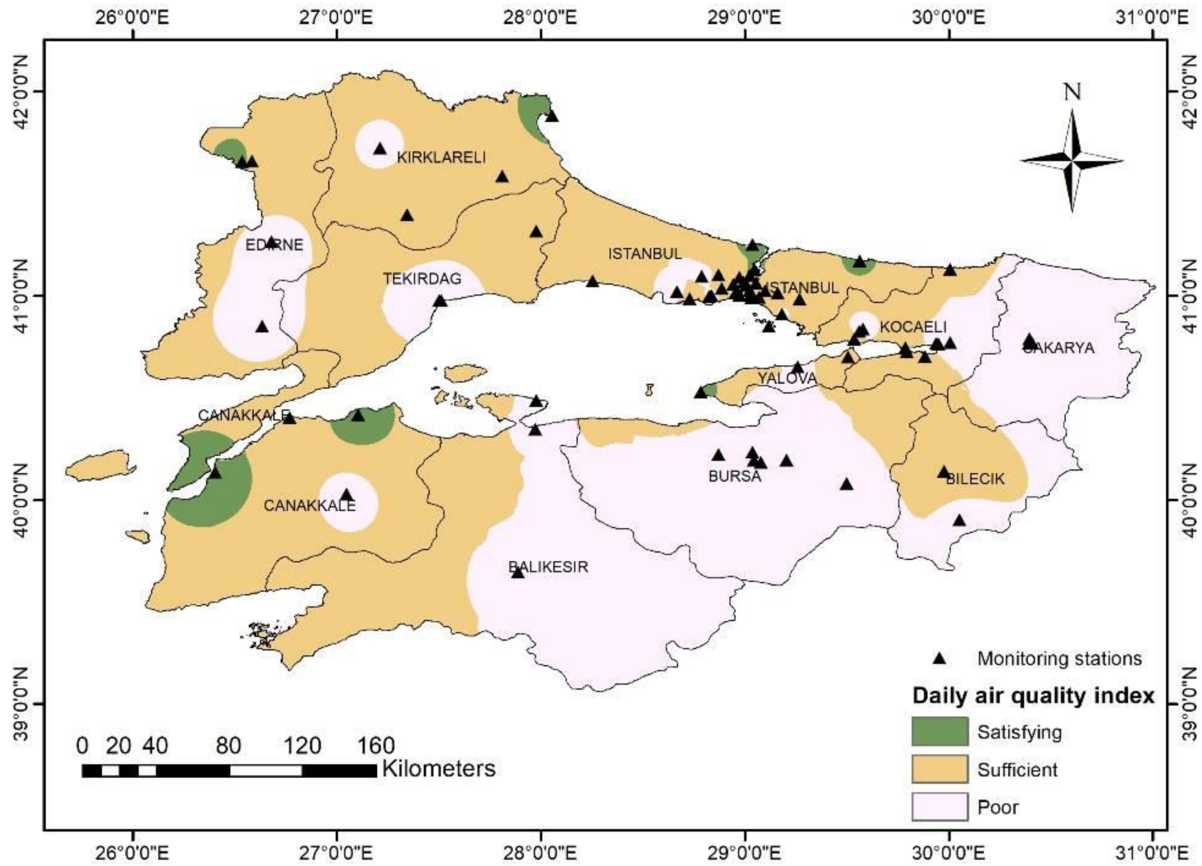

Figure 5: Daily air quality index map of Marmara region

4. Conclusion

In this study, the relationships between the emission of air pollutants in the atmosphere of the Marmara region and environmental variables such as spatial, meteorological, and anthropogenic were determined. Two different AQIs, including ASI and DAQx were employed to assess the air quality in the region.

The results demonstrated that, in parallel to increasing industrialization and traffic density, air pollution improved from the west to the east in the region. Human-related factors in the study area, such as Popdist, Popcou, and Vhcl, were the most responsible for the air pollutants, except CO, affected by only meteorological factors such as Prec, WS, and RH. Those factors also affected the other contaminants, which means that global climate change in the future can adversely affect air quality in the Marmara region with increasing temperature and decreasing precipitation. The ASI and DAQx values indicated that the air quality in the region exhibited distinct air stress and sufficient, respectively. The pollutants with the greatest effect on ASI and DAQx were PM10, O3, and NOx. Results from this study can be used as a base in regions with no monitoring stations.

The findings and outcomes could contribute to understanding and evaluating the air quality in the region and could be used as a base for further studies.

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