



# Examination of the Population Density Impact on Major Air Pollutants: A Study in the Case of Germany

Kamyar Fuladlu and Haşim Altan

## Abstract

**Background:** Today, there is a profound shift in the study of atmospheric pollutants at an urban scale especially due to their negative effects on humans and the environment. Atmospheric pollutants are emitted as a result of rapid urbanization, burning fossil fuels, deforestation, and agricultural intensification. The majority of studies believe cities have both the highest pollution rates and the highest impact targets. Unfortunately, the alteration of atmospheric pollutant patterns was faster than planners were able to come up with solutions. Major Air Pollutants (MAPs) are considered one of the important groups of atmospheric pollutants. Nitrogen Dioxide (NO<sub>2</sub>) and Sulfur Dioxide (SO<sub>2</sub>) are the main MAPs, which are released from road transport and are mostly exhaust emissions arising from fuel combustion. **Aim and Method:** Until a few years ago, monitoring MAPs, including NO<sub>2</sub> and SO<sub>2</sub> pollutants, was not as easy as today. Recently, the Sentinel-5 Precursor (S5P) satellite was successfully launched and scenes were released. Therefore, monitoring MAPs with the use of Remote Sensing (RS) and Geographical Information System (GIS) became possible. Accordingly, the current study aims to monitor NO<sub>2</sub> and SO<sub>2</sub> pollutants in the case of Germany as a country scale. Besides, this study has examined the relationship between the population density; NO<sub>2</sub> and SO<sub>2</sub> pollutants with the use of RS and GIS on the same scale as the use of a regression model. **Result:** Obviously, the concentration of the NO<sub>2</sub> and SO<sub>2</sub> pollutants over the cities is a result of mutual complex factors like meteorological situation, geographical

location, population density, and land-use land-cover. Therefore, it cannot be stated that the population density contributes to the increase of pollutants.

## Keywords

Germany • Major air pollutants • Nitrogen dioxide • Remote sensing • Sentinel-5 precursor satellite • Sulfur dioxide

## 1 Introduction

The potential of the urban area over the past centuries made it a living destination for many people. The United Nations estimated two-thirds of the world population by 2050, which will be living in urban areas (United Nations, 2019). Rapid urban development threatens sustainability, and to obtain environmental sustainability further challenges will be required (United Nations, 2015). At the beginning of the twenty-first century, rapid urban growth resulted in the transformation of the natural environment to the built-up area. An increase in population and demand for housing puts pressure on land cover. Hence today, the urban areas occupied 2% of the world's land, and those amounts of urban lands are responsible for consuming 75% of the world's energies and resources (Pacione, 2009). The main reasons could be addressed to unplanned, single-use, low-density, less accessible, and rapid urban development (Fuladlu, 2019, 2020; Fuladlu et al., 2018b, 2021). Cities become complicated as there are a variety of problems, including traffic congestion, urban pollution, waste and water management, resource management, social inequality, human health, and public security (Chourabi et al., 2012; Khan et al., 2013; Marceau, 2008; Neirotti et al., 2014). In microscale analysis, there are seven important environmental parameters that are effective; namely, “geographical location, meteorological situation, urban form, surface materials, amount of

K. Fuladlu (✉)

Department of Architecture, Faculty of Architecture, Eastern Mediterranean University, 99628 Famagusta, Cyprus  
e-mail: [kamyar\\_fuladlu@yahoo.com](mailto:kamyar_fuladlu@yahoo.com)

H. Altan

Department of Architecture, Faculty of Design, Arkin University of Creative Arts and Design, 99300 Kyrenia, Cyprus

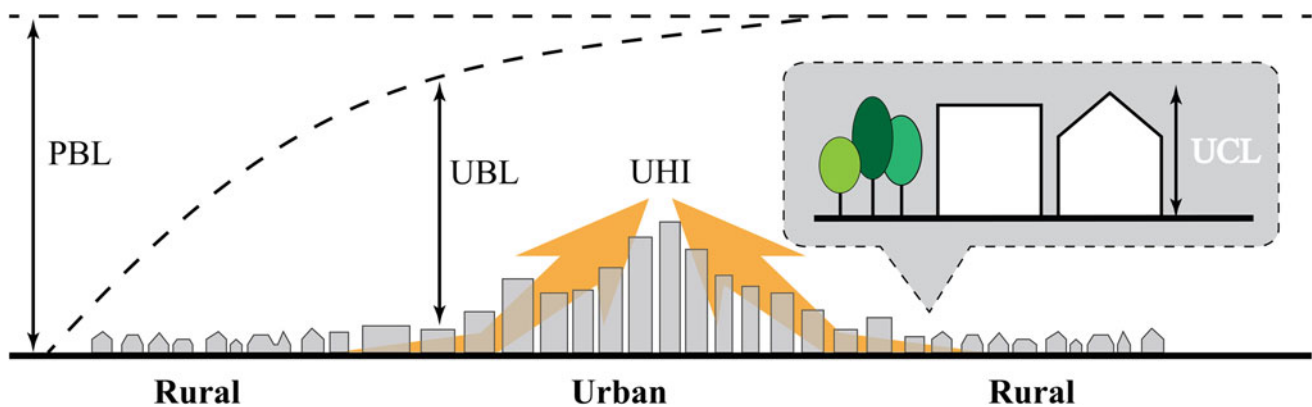
vegetation and watershed, and anthropogenic pollution” (Fuladlu, 2021).

Besides, burning fossil fuels, deforestation, and agricultural intensification are threatening the environment, and are known as the source of anthropogenic pollutants. Unfortunately, the alteration of pollutant patterns was faster than planners were able to come up with a solution (Marsh and Smith 1996). Fundamentally, the nature of cities is shaped by concentrations of humans, materials, and activities. Therefore, they have both the highest pollution rates and the highest impact targets (Fenger, 1999). Additionally, the gradient concentration of the particulate increases according to the land-use density from the countryside toward the core of the urban area. In this sense, the particulate levels in the urban areas are usually two to three times greater than that of the suburban areas, and five times greater than that of the countryside (Marsh & Grossa, 1996). There are several reasons for the accumulation of pollutants in cities. According to Zabalza et al. (2007) at the local level atmospheric pollutants are a major urban problem due to the following factors; (a) majority of the anthropogenic sources are within the urban area, (b) the effect of Urban Heat Island (UHI) to cities (Fig. 1), and (c) concentration of the human in the urban area. Therefore, there is a profound shift in the study of atmospheric pollutants at an urban scale especially due to their negative effects on humans and the environment.

For instance, Weng and Yang (2006) “in the case of Guangzhou city in southern China, by using the Geographic Information System (GIS) approach, examined the spatial pattern of air pollution and land use, and the results showed that the spatial patterns of air pollutants probed were positively correlated with urban built-up density”. Feizizadeh and Blaschke (2013) in the case of Tabriz city in Iran found a positive correlation among land-cover, land surface temperature, and air pollutants. Kaplan et al. (2019) in the case of Turkey found a significant correlation between population density and maximum tropospheric Nitrogen dioxide ( $\text{NO}_2$ ). Fuladlu and Altan (2021) in the case of Tehran province with

the use of Remote Sensing (RS), GIS, and Moving Average (MA) showed that Sulfur dioxide ( $\text{SO}_2$ ) and  $\text{NO}_2$  are mainly concentrated in the Tehran metropolis and the core urban area. The air pollutants are categorized into three groups; (a) Major Air Pollutants (MAPs) include “ $\text{SO}_2$ ,  $\text{NO}_2$ , Carbon monoxide (CO), Particular matter (PM) lead (Pb), and Ozon ( $\text{O}_2$ ), which are frequently used as indicators of air pollutants in ambient air. MAPs are target species due to their negative impact on human health and vegetation” (European Union Council Directive 96/62/EC). (b) Hazardous Air Pollutants (HAPs) include physical, chemical, and biological agents. Generally, HAPs in comparison to MAPs are in smaller concentrations and seem regularly more localized (Fenger, 1999; Flemming et al., 2005; Wiederkehr & Yoon, 1998; Zabalza et al., 2007). (c) Heat could be considered as a pollutant since the built-up area tends to be warmer than the adjacent area. The generation of heat in an urban area is the climatic reaction to disruptions caused by urban development known as UHI (Fuladlu et al., 2018a; Marsh & Grossa, 1996). The urbanization process transforms the natural material into artificial with the minimum ability of evapotranspiration. This results in a partitioning of energy into sensible fluxes rather than latent heat fluxes. The UHI effect was studied at two distinct layers, Urban Canopy Layer (UCL) and Urban Boundary Layer (UBL). The UCL extends vertically up to the roof level, where the UBL is situated directly above the UCL (Fig. 1) (Oke, 1973, 1976, 1982, 2011).

Among the air pollutants studied, majority have focused on  $\text{SO}_2$  and  $\text{NO}_2$  due to the environmental consequences, for instance,  $\text{SO}_2$  is a major acid rain precursor, which contributes to acidic deposition in terrestrial ecosystems as dry-deposited gas (Cox, 2003; Meng et al., 2008).  $\text{SO}_2$  oxidation product, Sulfate, plays a significant role in the radiative forcing of the climate. Similarly,  $\text{NO}_2$  is of particular concern, as it plays a crucial role in atmospheric chemistry by participating in the formation of tropospheric  $\text{O}_3$ , peroxyacyl nitrate, and nitrate aerosols (Meng et al., 2008).  $\text{SO}_2$  and  $\text{NO}_2$  are short-lived trace gases that have key



**Fig. 1** Planetary Boundary Layer (PBL), Urban Boundary Layer (UBL), Urban Canopy Layer (UCL), and Urban Heat Island (UHI)

roles in tropospheric chemistry. Besides, SO<sub>2</sub> and NO<sub>2</sub> are involved in the formation of secondary aerosol particles (Krotkov et al., 2016; Xue et al., 2020). “Major sources of NO<sub>x</sub> (NO<sub>x</sub> = NO + NO<sub>2</sub>) include fossil fuel combustion, mediated biomass burning, industrial and transportation emissions, and lightning” (Krotkov et al., 2016; Xue et al., 2020). “NO<sub>2</sub> affects atmospheric oxidation rates participating in the formation of surface ozone” (Krotkov et al., 2016; Meng et al., 2008). “The natural source of SO<sub>2</sub> is volcanic eruptions, which can release a large amount of SO<sub>2</sub> above the Planetary Boundary Layer (PBL). The anthropogenic source of SO<sub>2</sub> was burning sulfur-contaminated fossil fuels and the refinement of sulfide ores, which mainly concentrated in the PBL” (Fig. 1) (Brunelli et al., 2007; Krotkov et al., 2016; Xue et al., 2020).

For decades, new dimensions of RS and its ability to integrate with GIS have created new opportunities for monitoring and interpretation of the spatial dataset. Besides, RS and GIS, when used together, are recognized as a strong and outstanding tool for monitoring alterations in the spatial dataset. The advantage is the cost efficiency of RS and GIS as a method of monitoring. Moreover, RS and GIS are derived from the accessibility of data collected by thousands of satellites orbiting the planet. However, until a few years ago monitoring MAPs from a satellite was not as easy as today. Recently the Sentinel-5 Precursor (S5P) satellite was successfully launched by scene release. Accordingly, the S5P satellite aims to fill in the data gap and to provide data continuity between the retirement of the Envisat satellite and NASA’s Aura mission and the launch of S5P satellite. The S5P satellite objectives are to provide operational space-borne observations in support of the operational monitoring Air Quality, O<sub>2</sub>, Surface Ultraviolet, and Climate. Besides, it will provide measurements of O<sub>2</sub>, NO<sub>2</sub>, SO<sub>2</sub>, CO, Formaldehyde, Aerosol, Methane, and Clouds.

Until now, a systematic review of the literature provides a focus on the atmospheric pollutants in the cities. Literature includes the main sources of the atmospheric pollutants, classification, and the S5P satellite as a tool for monitoring the pollutants, especially MAPs. The current study firstly aims to monitor NO<sub>2</sub> and SO<sub>2</sub> pollutants in the case of Germany as a country scale. Secondly, this study examines the relationship between the population density, NO<sub>2</sub> and SO<sub>2</sub> pollutants with the use of RS and GIS on the same scale with the use of a regression model. The reasons to choose Germany for a case in this study were:

- A. Germany has the largest economy in Europe, on a global scale, it has leading several industrial and technological sectors.
- B. Germany as a highly developed country provides census, statistical dataset, and temporal map on different levels, which make the base for any study.
- C. Germany with an area of 357,022 km<sup>2</sup> is suitable for study with the S5P satellite resolution.

---

## 2 Materials and Methods

### 2.1 Case Study

“Germany, officially the Federal Republic of Germany, is a country in Central and Western Europe. It is located between the Baltic and North seas to the north, and the Alps to the south. It borders Denmark to the north, Poland and the Czech Republic to the east, Austria and Switzerland to the south, and France, Luxembourg, Belgium, and the Netherlands to the west”. Germany comprises sixteen federal states, each state has its state constitution and is largely autonomous regarding its internal organization. By 2017 Germany is divided into 402 districts at municipal levels; these consist of 295 rural districts and 107 urban districts. According to Germany government estimates on 31st December 2018, the German population was about 83,040,944 (Wikipedia, 2020).

The satellite is a material of the study chosen according to the published population estimation by the German government on 31st December 2018. Therefore, the population date is considered as a groundwork for the current study. The S5P satellite RS was utilized to acquire data for NO<sub>2</sub> and SO<sub>2</sub> pollutants using the following means:

- (a) The twelve Level 2 (level-two) senses for each pollutant were acquired from the S5P satellite; the twelve senses are good enough to present the overall condition of the year and to increase the study accuracy.
- (b) The last day of each month was chosen for the period of 31st October 2018 to 30th September 2019.

The detailed steps are described under the next sections and the overall study methodology diagram is summarized in Fig. 2.

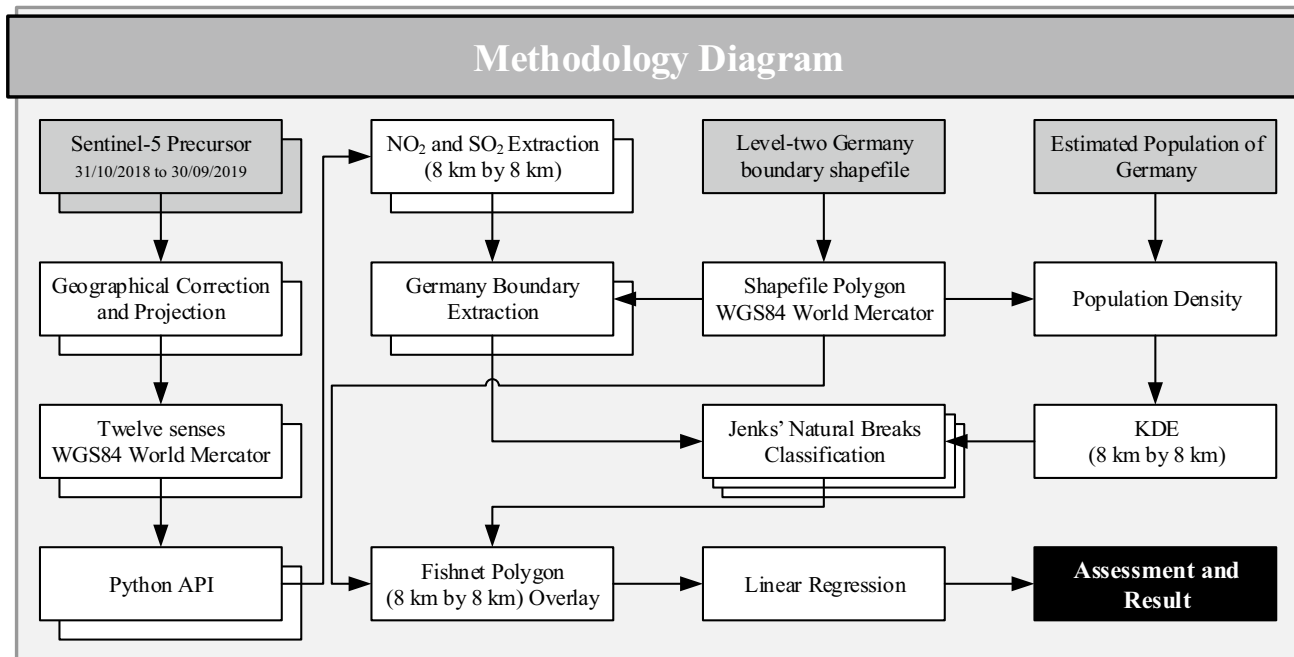


Fig. 2 Methodology diagram

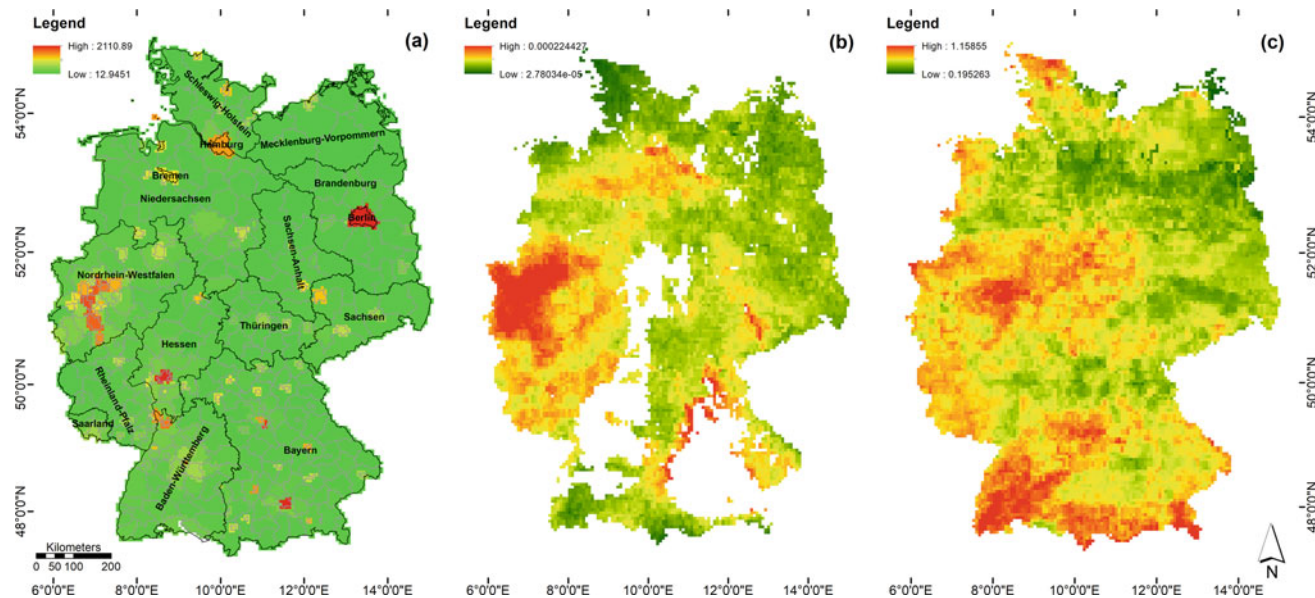
## 2.2 Pre-Processing

The population density raster developed with the use of the Level 2 Germany boundary shapefile. The shapefile projection was WGS84 World Mercator and had 403 polygons including rural, urban districts, and water bodies. The estimated population dataset was integrated into the shapefile attribute based on the records. The population density was calculated in GIS for each district and rasterized according to the S5P satellite resolution (8 km by 8 km). The process was performed with the use of Kernel Density Estimation (KDE). The KDE is known as an outstanding method which facilitates a cell-by-cell means for the future correlation between rasters (Fotheringham et al., 2000; O'Sullivan & Unwin, 2010; Silverman, 1998). The KDE outcome is classified with the use of Jenks' natural breaks method as shown in Fig. 3a.

"Time-series take place in a wide range of phenomena" (Salcedo et al., 1999). "Air quality monitoring is an example of an environmental time-series study. The method commonly is used to estimate environmental parameters and based on classical descriptive statistics, but due to the high variability associated with air quality data and the low signal-to-tonnage ratio of existing measurements, this value is relatively limited. Time-series studies may be a good tactic to avoid these troubles by agreeing to the identification of hidden deterministic behavior and thus contributing to an understanding of origin and consequence associations in

environmental and urban problems" (Schwartz & Marcus, 1990). "Time-series still form the basis of decomposition methods; a smoothing technique is required to apply on time-series to remove the fine-grained variation between time steps. MA is a simple and common type of smoothing used in time-series analysis and is a calculation for analyzing data points by creating an average series of different subsets from a big dataset" (Fuladlu & Altan, 2021).

The NO<sub>2</sub> and SO<sub>2</sub> rasters developed with the use of the twelve senses to represent points of time for each of the pollutants. As stated earlier, all the required senses are acquired from the S5P satellite. The python API was integrated into the GIS to minimize human errors and save time during the big data interpretation. Accordingly, the geographical correction was applied to all senses to minimize the distortion, and later all the senses were projected to the WGS84 World Mercator. The NO<sub>2</sub> tropospheric (mol/m<sup>2</sup>) and SO<sub>2</sub> total (mol/m<sup>2</sup>) bands were used for calculating the MA of each pollutant. The MA of each pollutant is accurately calculated from twelve senses with the use of the spatial analyst function of GIS. As a result, two rasters were created for NO<sub>2</sub> and SO<sub>2</sub> pollutants, all the pixels beyond the Germany boundary shapefile were eliminated from the rasters and classified with the use of Jenks' natural breaks method as shown in Fig. 3b and c. About 18% of Fig. 3b is unusable (blank area) due to the no-data pixel of the sources, which is considered as a study bias.



**Fig. 3** Germany **a** population density ( $\#/km^2$ ), **b**  $NO_2$  ( $mol/m^2$ ), and **c**  $SO_2$  ( $mol/m^2$ )

### 3 Results and Analysis

Different approaches exist to quantify the raster's data. However, the current study experimentally puts its approach into practice. According to the methodology diagram (Fig. 2), all rasters are made according to the resolution of the S5P satellite and there is no need to resample it. Therefore, a fishnet is created according to the German boundary with the same resolution and projection in GIS. The required fields added to the fishnet attribute overlay the rasters of population density,  $NO_2$ , and  $SO_2$  pollutant values. The records of those fields were used to develop the future correlation matrix between the population density,  $NO_2$ , and  $SO_2$  pollutants. Accordingly, the cell-by-cell examination is performed with the use of the Pearson two-tailed correlation matrix for 22,750 cells and the results are presented in Table 1.

The correlation between population density,  $NO_2$  and  $SO_2$  pollutants visualized with the use of the scatter plot and the trend of each plot is shown with linear regression (Fig. 4).

The relationship between population density and pollutants is quantified with the use of linear regression and equation, which are written for each pollutant (Table 2).

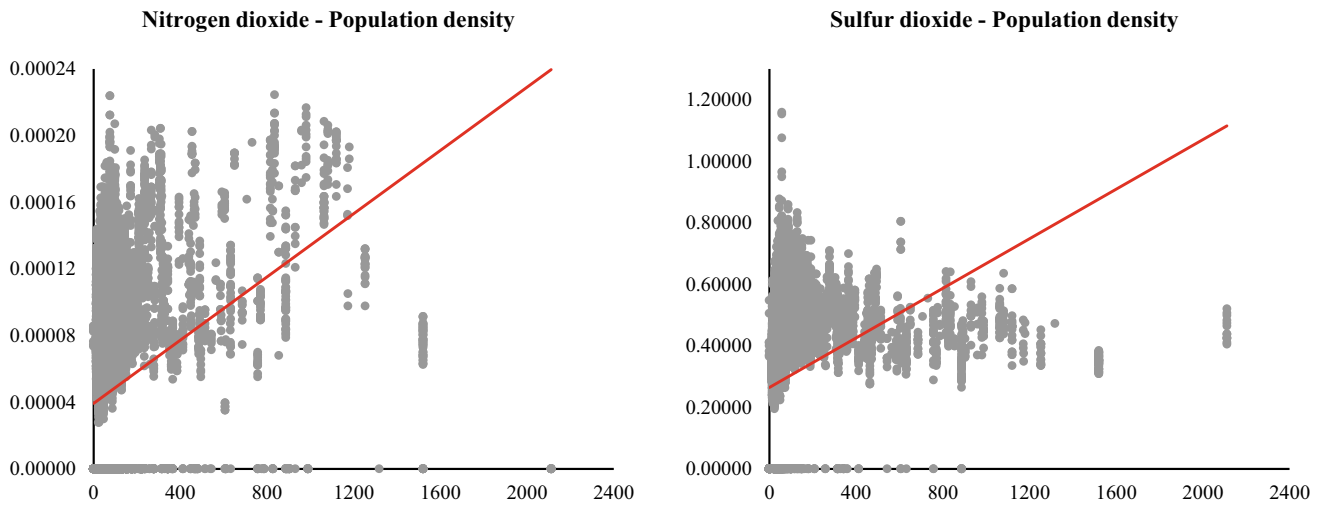
Based on the correlation matrix (Table 1; Fig. 4), there is a correlation at the 0.01 level between the variables. Accordingly, a positive correlation was noted between the population density and  $NO_2$  pollution ( $r = 0.314$ ,  $p < 0.01$ ). Likewise, the population density and  $SO_2$  pollution had a positive correlation too ( $r = 0.276$ ,  $p < 0.01$ ). Besides, a positive correlation between both  $NO_2$  and  $SO_2$  pollutants is outstanding ( $r = 0.663$ ,  $p < 0.01$ ). A one-way ANOVA (Table 2) was conducted to compare the effect of the pollutants on population density. The variance analysis showed that the effect of  $NO_2$  on population density existed, and the effect of  $SO_2$  on population density existed. In summary, there is a positive correlation between population density,  $NO_2$  and  $SO_2$  pollutants. However, the mean of pollutants is relatively minimized in districts with a high population density (Fig. 3a, b, and c).

**Table 1** Correlation matrix of the variables

Variables		Population density	Nitrogen dioxide	Sulfur dioxide
Population density	Pearson correlation	1		
	N	22,750		
Nitrogen dioxide	Pearson correlation	0.314**	1	
	N	22,750	22,750	
Sulfur dioxide	Pearson correlation	0.276**	0.663**	1
	N	22,750	22,750	22,750

\*\*Correlation is significant at the 0.01 level (two-tailed)





**Fig. 4** Scatter graph for population density (#/Km<sup>2</sup>), NO<sub>2</sub> (mol/m<sup>2</sup>), and SO<sub>2</sub> (mol/m<sup>2</sup>)

**Table 2** Linear regression equations for population density and each pollutant

Pollutants	Equation	R	R <sup>2</sup>	df1	df2	F. change	Sig. F. change
NO <sub>2</sub>	Population density = 20.495 × NO <sub>2</sub> 1,038,659.509	0.314	0.099	1	22,748	2486.557	0.000
SO <sub>2</sub>	Population density = 12.703 × SO <sub>2</sub> + 189.425	0.276	0.076	1	22,748	1878.813	0.000
Both	Population density = (772,155.898 × NO <sub>2</sub> ) (83.301 × SO <sub>2</sub> ) × + 8.355	0.327	0.107	2	22,747	1359.989	0.000

## 4 Discussion

According to the outcome (Fig. 3) München 2110.89 and after Berlin 1520.81 had maximum population density among the German districts. However, the maximum concentration of the pollutants was mainly located in the west and south-west of Germany (Fig. 3b and c). Likewise, NO<sub>2</sub> is seen at Nordrhein-Westfalen state while SO<sub>2</sub> is seen at Baden-Württemberg, Bayern, and Schleswig-Holstein state. Although Tables 1 and 2; Fig. 4 depict an overall positive correlation between the population density, NO<sub>2</sub> and SO<sub>2</sub> pollutants, this correlation was not significant as expected. The concentration of NO<sub>2</sub> and SO<sub>2</sub> pollutants over the cities as a result of mutual complex factors like meteorological situation, geographical location, population density, and land-use land-cover (Weng & Yang, 2006). Therefore, it cannot be stated that the population density contributes to the increase of pollutants.

As stated previously, the main source of SO<sub>2</sub> and NO<sub>2</sub> pollutants is fossil fuel combustion, which are released by the manufacturing industries. A quick look over Germany depicts that, majority of the manufacturing and industries such as Rolls-Royce, MTU Aero Engines, Cassidian, Astrium, Airbus, BMW, Daimler, ThyssenKrupp, Otto

Fuchs, OHB, and etcetera mainly located in Hamburg, Niedersachsen, Hessen, Baden-Württemberg, and Bayern states; whereas the pollutants are mainly concentrated (Fig. 3b and c). Therefore, proximity to manufacturing and industries more than population density can be attributed to the concentration of NO<sub>2</sub> and SO<sub>2</sub> pollutants. Similarly, NASA (2020) and European space agency pollution monitoring satellites by the end of February 2020 had detected significant decreases in NO<sub>2</sub> pollution over Wuhan, China. NASA scientists confirm the significant decrease of NO<sub>2</sub> pollution in eastern and central China in comparison to the previous years. Decrease of NO<sub>2</sub> pollution over Wuhan attributes to the Chinese quarantines by 23rd January 2020. Accordingly, Chinese authorities had shut-down transportation and local businesses of Wuhan to reduce the spread of the COVID-19 pandemic.

## 5 Conclusions

The study of atmospheric pollutants due to their negative impacts on humans and the environment becomes a topic for discussion. Until now, different studies confirm the role of population concentration on MAP emissions. Likewise, the current study was put forward to provide comprehensive

reviews of atmospheric pollutants. Besides this study aims to monitor the MAPs including NO<sub>2</sub> and SO<sub>2</sub> pollutants in the case of Germany as a country scale. Moreover, the study tries to quantify the relationship between the population density, NO<sub>2</sub> and SO<sub>2</sub> pollutants with the use of RS and GIS on the same scale with the use of a regression model. The S5P satellite RS was utilized to retrieve the necessary data for each NO<sub>2</sub> tropospheric (mol/m<sup>2</sup>), and SO<sub>2</sub> total (mol/m<sup>2</sup>) over Germany.

The  $\bar{x}$  of each pollutant was accurately calculated from twelve senses for the period of 31st October 2018 to 30th September 2019. The value is compared with the Level 2 population density of Germany. Thus, the results depict the positive correlations between the population density, NO<sub>2</sub> and SO<sub>2</sub> pollutants. However, this relationship is not as expected as the concentration of pollutants that was found mainly in the states where the manufacturing industries are located. Further studies are required to investigate the correlation of MAPs, and land surface temperature with population density and other factors, which are contributing to environmental pollution.

**Acknowledgements** The authors wish to acknowledge Canay Ataöz, Head of Technical Services of the Library at Eastern Mediterranean University, Aroscha Architecture and Urban Research Development and Technology for providing the resources and materials that supported the author's execution of this study.

#### Funding

The authors received no financial support for the research, authorship, and publication of this manuscript from agencies in the public, commercial, or not-for-profit sectors.

#### Availability of Data and Materials

All data generated or analyzed during this research are included in this manuscript.

#### Competing Interests

The authors declare that they have no competing interests.

## References

- Brunelli, U., Piazza, V., Pignato, L., Sorbello, F., & Vitabile, S. (2007). Two-days ahead prediction of daily maximum concentrations of SO<sub>2</sub>, O<sub>3</sub>, PM<sub>10</sub>, NO<sub>2</sub>, CO in the urban area of Palermo Italy. *Atmospheric Environment*, 41(14), 2967–2995. <https://doi.org/10.1016/j.atmosenv.2006.12.013>
- Chourabi, H., Nam, T., Walker, S., Gil-Garcia, J. R., Mellouli, S., Nahon, K., Pardo, T. A., & Scholl, H. J. (2012). *Understanding Smart Cities: An Integrative Framework*. Paper presented at the 2012 45th Hawaii International Conference on System Sciences, Maui, HI, USA. <https://doi.org/10.1109/HICSS.2012.615>
- Cox, R. M. (2003). The use of passive sampling to monitor forest exposure to O<sub>3</sub>, NO<sub>2</sub> and SO<sub>2</sub>: a review and some case studies. *Environmental Pollution*, 126(3), 301–311. [https://doi.org/10.1016/S0269-7491\(03\)00243-4](https://doi.org/10.1016/S0269-7491(03)00243-4)
- Feizizadeh, B., & Blaschke, T. (2013). Examining urban heat Island relations to land use and air pollution: multiple endmember spectral mixture analysis for thermal remote sensing. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 6(3), 1749–1756. <https://doi.org/10.1109/jstars.2013.2263425>
- Fenger, J. (1999). Urban air quality. *Atmospheric Environment*, 33(29), 4877–4900. [https://doi.org/10.1016/S1352-2310\(99\)00290-3](https://doi.org/10.1016/S1352-2310(99)00290-3)
- Flemming, J., Stern, R., & Yamartino, R. J. (2005). A new air quality regime classification scheme for O<sub>3</sub>, NO<sub>2</sub>, SO<sub>2</sub> and PM<sub>10</sub> observations sites. *Atmospheric Environment*, 39(33), 6121–6129. <https://doi.org/10.1016/j.atmosenv.2005.06.039>
- Fotheringham, A. S., Brunson, C. F., & Charlton, M. (2000). *Quantitative Geography: Perspectives on Spatial Data Analysis* (1st ed.): SAGE Publications Ltd.
- Fuladlu, K. (2019). Urban Sprawl Negative Impact: Enkomi Return Phase. *Journal of Contemporary Urban Affairs*, 3(1), 44–51. <https://doi.org/10.25034/jcua.2018.4709>
- Fuladlu, K. (2020). Urban sprawl measurement with use of VMT Pattern: A longitudinal method in case of Famagusta. *International Journal of Advanced and Applied Sciences*, 7(5), 12–19. <https://doi.org/10.21833/ijaas.2020.05.003>
- Fuladlu, K. (2021). Environmental parameters for campus outdoor space: A microclimate analysis of the eastern mediterranean university (EMU) campus. *Journal of Green Building*, 16(3), 217–236. <https://doi.org/10.3992/jgb.16.3.217>
- Fuladlu, K., & Altan, H. (2021). Examining land surface temperature and relations with the major air pollutants: A remote sensing research in case of Tehran. *Urban Climate*, 39, 100958. <https://doi.org/10.1016/j.uclim.2021.100958>
- Fuladlu, K., Riza, M., & İlkan, M. (2018a). *The Effect of Rapid Urbanization On the Physical Modification of Urban Area*. Paper presented at the The 5th International Conference on Architecture and Built Environment with AWARDS S.ARCH 22–24 May 2018a, Venice, Italy.
- Fuladlu, K., Riza, M., & İlkan, M. (2018b). *Impact of Urban Sprawl: The Case of the Famagusta, Cyprus*. Paper presented at the 1st Regional Conference: Cyprus Network of Urban Morphology CyNUM 16–18 May 2018b, Nicosia, Cyprus.
- Fuladlu, K., Riza, M., & İlkan, M. (2021). Monitoring urban sprawl using time-series data: Famagusta region of Northern Cyprus. *SAGE Open*, 11(2), 21582440211007464. <https://doi.org/10.1177/21582440211007465>
- Kaplan, G., Avdan, Z. Y., & Avdan, U. (2019). Spaceborne nitrogen dioxide observations from the sentinel-5P TROPOMI over Turkey. *Proceedings*, 18(1). <https://doi.org/10.3390/ECRS-3-06181>
- Khan, Z., Anjum, A., & Kiani, S. L. (2013). *Cloud Based Big Data Analytics for Smart Future Cities*. Paper presented at the 2013 IEEE/ACM 6th International Conference on Utility and Cloud Computing, Dresden, Germany. <https://doi.org/10.1109/UCC.2013.77>
- Krotkov, N. A., McLinden, C. A., Li, C., Lamsal, L. N., Celarier, E. A., Marchenko, S. V., Swartz, W. H., Bucsela, E. J., Joiner, J., Duncan, B. N., Boersma, K. F., Veefkind, J. P., Levelt, P. F., Fioletov, V. E., Dickerson, R. R., He, H., Lu, Z., & Streets, D. G. (2016). Aura OMI observations of regional SO<sub>2</sub> and NO<sub>2</sub> pollution changes from 2005 to 2015. *Atmospheric Chemistry and Physics*, 16(7), 4605–4629. <https://doi.org/10.5194/acp-16-4605-2016>
- Marceau, J. (2008). Introduction: Innovation in the city and innovative cities. *Innovation: Management, Policy & Practice*, 10(2–3), 136–145. <https://doi.org/10.5172/impp.453.10.2-3.136>
- Marsh, W. M., & Grossa, J. M. (1996). *Environmental Geography: Science, Land Use, and Earth Systems* (1st ed.). John Wiley & Sons.
- Meng, Z. Y., Ding, G. A., Xu, X. B., Xu, X. D., Yu, H. Q., & Wang, S. F. (2008). Vertical distributions of SO<sub>2</sub> and NO<sub>2</sub> in the lower atmosphere in Beijing urban areas China. *Science of the Total Environment*, 406(1–3), 105–112. <https://doi.org/10.1016/j.scitotenv.2008.07.011>

- Environment*, 390(2), 456–465. <https://doi.org/10.1016/j.scitotenv.2007.10.012>
- NASA. (2020). Airborne nitrogen dioxide plummets over China. <https://earthobservatory.nasa.gov/images/146362/airborne-nitrogen-dioxide-plummets-over-china>.
- Neirotti, P., Marco, A. D., Cagliano, A. C., Mangano, G., & Scorrano, F. (2014). Current trends in smart city initiatives: Some stylised facts. *Cities*, 38, 25–36. <https://doi.org/10.1016/j.cities.2013.12.010>
- O'Sullivan, D., & Unwin, D. (2010). *Geographic Information Analysis* (2nd ed.). New Jersey: John Wiley & Sons. <https://doi.org/10.1002/9780470549094>.
- Oke, T. R. (1973). City size and the urban heat island. *Atmospheric Environment* (1967), 7(8), 769–779. [https://doi.org/10.1016/0004-6981\(73\)90140-6](https://doi.org/10.1016/0004-6981(73)90140-6).
- Oke, T. R. (1976). The distinction between canopy and boundary-layer urban heat islands. *Atmosphere*, 14(4), 268–277. <https://doi.org/10.1080/00046973.1976.9648422>
- Oke, T. R. (1982). The energetic basis of the urban heat island. *Quarterly Journal of the Royal Meteorological Society*, 108(455), 1–24. <https://doi.org/10.1002/qj.49710845502>
- Oke, T. R. (2011). Urban heat islands. In I. Douglas, D. Goode, M. Houck, & R. Wang (Eds.), *The Routledge Handbook of Urban Ecology* (1st ed., pp. 120–131). Oxon: Abingdon: Routledge. <https://doi.org/10.4324/9780203839263.ch11>.
- Pacione, M. (2009). *Urban Geography: A Global Perspective* (3rd ed.). London: Routledge. <https://doi.org/10.4324/9780203881927>.
- Salcedo, R. L. R., Alvim-Ferraz, M. D. C., Alves, C. A., & Martins, F. G. (1999). Time-series analysis of air pollution data. *Atmospheric Environment*, 33(15), 2361–2372. [https://doi.org/10.1016/S1352-2310\(99\)80001-6](https://doi.org/10.1016/S1352-2310(99)80001-6)
- Schwartz, J., & Marcus, A. (1990). Mortality and air pollution in London: A time series analysis. *American Journal of Epidemiology*, 131(1), 185–194. <https://doi.org/10.1093/oxfordjournals.aje.a115473>
- Silverman, B. W. (1998). *Density Estimation for Statistics and Data Analysis*. Routledge. <https://doi.org/10.1201/9781315140919>
- United Nations. (2015). *World Urbanization Prospects: The 2014 Revision*. (ST/ESA/SER.A/366). P. D. Department of Economic and Social Affairs. New York. <https://population.un.org/wup/Publications/Files/WUP2014-Report.pdf>.
- United Nations. (2019). *World Urbanization Prospects: The 2018 Revision*. (ST/ESA/SER.A/420). P. D. Department of Economic and Social Affairs. New York. <https://population.un.org/wup/Publications/Files/WUP2018-Report.pdf>.
- Weng, Q., & Yang, S. (2006). Urban air pollution patterns, land use, and thermal landscape: An examination of the linkage using GIS. *Environmental Monitoring and Assessment*, 117(1–3), 463–489. <https://doi.org/10.1007/s10661-006-0888-9>
- Wiederkehr, P., & Yoon, S.-J. (1998). Air quality indicators. In J. Fenger, O. Hertel, & F. Palmgren (Eds.), *Urban Air Pollution - European Aspects* (pp. 403–418). Dordrecht: Springer Netherlands. <https://doi.org/10.1007/978-94-015-9080-8>
- Wikipedia. (2020). Germany, <https://en.wikipedia.org/wiki/Germany>, Accessed 6 Mar 2020.
- Xue, R., Wang, S., Li, D., Zou, Z., Chan, K. L., Valks, P., Saiz-Lopez, A., & Zhou, B. (2020). Spatio-temporal variations in NO<sub>2</sub> and SO<sub>2</sub> over Shanghai and Chongming Eco-Island measured by Ozone Monitoring Instrument (OMI) during 2008–2017. *Journal of Cleaner Production*, 258, 120563. <https://doi.org/10.1016/j.jclepro.2020.120563>
- Zabalza, J., Ogulei, D., Elustondo, D., Santamaría, J. M., Alastuey, A., Querol, X., & Hopke, P. K. (2007). Study of urban atmospheric pollution in Navarre (Northern Spain). *Environmental Monitoring and Assessment*, 134(1–3), 137–151. <https://doi.org/10.1007/s10661-007-9605-6>