

SELECTED LAND COVER FACTORS AS A DETERMINANT OF DIFFERENCES IN PARTICULATE MATTER CONCENTRATIONS – A CASE STUDY OF WARSAW, POLAND

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Abstract

An important aspect of modelling is the choice of descriptor variables. This study extended typical modelling of PM₁₀ concentrations based on meteorological parameters with additional variables related to the spatial characteristics of the environment. Meteorological parameters have smaller spatial gradients, while land cover is point-specific. Daily meteorological data from the Warsaw Chopin Airport (EPWA) and satellite land cover data from the Polish Space Agency were used to describe PM₁₀ concentrations at 5 air quality stations in Warsaw for 2021. The multilinear model developed in Gretl showed that significant factors increasing PM₁₀ concentrations included maximum daily temperature, duration of fog, haze, frost, and the proportion of artificial surfaces and coniferous tree cover within a 1 km radius of the stations. PM₁₀ concentrations were negatively correlated with increases in daily minimum temperature, duration of rainfall, snowfall, wind ≥ 10 m/s, and the proportion of deciduous tree cover and herbaceous vegetation. The use of land cover parameters improved the model's coefficient of determination for daily PM₁₀ average concentrations.

1. INTRODUCTION

Meteorological conditions have been identified as a primary factor influencing PM₁₀ concentrations, both directly and indirectly. The atmospheric dispersion of particulate matter is facilitated by meteorological parameters, which consequently act as drivers of particulate concentrations by virtue of their capacity to influence airborne particle transport and dispersion (Birinci et al., 2023; Cichowicz et al., 2020; Girotti et al., 2025; Grundström et al., 2015; Kirešová & Guzan, 2022). Wind direction and speed, in particular, have been shown to have a direct impact on the transport and dispersion of airborne particles. Furthermore, the frequency of air mass influx from specific directions has been demonstrated to correlate with particulate levels in several studies, thereby offering a more pro-

found understanding of the role of meteorological factors (H. Lu & Fang, 2002). The direction of wind plays a pivotal role in this context, as it can either exacerbate the concentration of pollutants when unfavourable conditions prevail or aid in their dispersion when wind speeds are high and directional flow is optimal for pollutant removal.

Concurrent with meteorological influences, advancements in remote sensing technology have facilitated the development of highly accurate land cover maps around monitoring stations (Probeck et al., 2021; United States Geological Survey, n.d.; Xian, 2007). These maps enable a more detailed understanding of the spatial environment surrounding air quality receptors, which can play a crucial role in understanding the variation in particulate concentrations across different areas within a city.

While traditional air quality models have frequently relied exclusively on meteorological data, recent research has demonstrated that land cover significantly impacts air quality outcomes (Y. Lu et al., 2023; Tao et al., 2013; W. Yang & Jiang, 2021). Numerous studies have developed multilinear models for predicting particulate matter concentrations based solely on meteorological parameters. However, it is evident that different air quality monitoring stations within the same city may exhibit varying levels of particulate concentrations, even under similar meteorological conditions (Yu et al., 2022). This discrepancy can be attributed to local variations in land cover and urban infrastructure.

The primary goal of this study is to develop a model that can explain the differences in PM_{10} concentrations at various monitoring stations within a city, particularly in areas with similar meteorological conditions. This model incorporates land cover data, specifically focusing on the surrounding environment within a 1 km radius of each monitoring station. The model integrates land cover factors, including the proportion of artificial surfaces, vegetation types, and urban structures, with the aim of identifying the spatial factors that influence PM_{10} levels and contribute to the observed discrepancies in concentrations across separate locations.

The approach presented here is innovative in that it considers both meteorological conditions and land cover features within a localized context, thereby looking to bridge the gap between traditional meteorological modelling of PM_{10} concentrations and spatially explicit models that account for the influence of land cover. The aim is to provide a more comprehensive understanding of how urban land use and environmental characteristics impact air quality, and to identify the key spatial factors that condition PM_{10} concentrations in urban areas. This work enhances the accuracy of PM_{10} prediction models and offers valuable insights for urban planning and air quality management.

2. MATERIALS AND METHODS

2.1. Study area

The research was conducted in the area of Warsaw, Poland. Warsaw is the capital of Poland, a city with an area of 517 km² at 78-121 m ASL located at the Vistula river banks (GUS, 2024). The main sources of PM_{10} emissions in Warsaw are individual heating, road traffic and industrial and construction activities.

Individual heating, especially during the heating season, is a significant source of PM_{10} emissions, mainly due to the fact that not all of the city is connected to the district heating network and the use of solid fuels in domestic stoves and boilers is often supplemented by illegal burning of waste in them (Badyda et al., 2020). Several important national roads with highway or expressway standards run through Warsaw. Especially, Warsaw is crossed by two east-west routes, the only highway connections in the country, which cross the largest river in Poland, the Vistula, making the Grot Rowecki Bridge the section of road with the highest traffic intensity in the country (GDDKiA, 2021), and the this traffic intensity has a significant impact on PM_{10} concentrations (Białowicz et al., 2023). As Poland is a developed but still developing country (Milek, 2018; Raszka et al., 2021), there is also a lot of investment going on in Warsaw, which means that industrial processes and intensive construction work increase PM_{10} concentrations in the air.

2.2. Meteorological data and air quality data

The meteorological data were downloaded from the Institute of Meteorology and Water Management National Research Institute Public Data (IMGW-PIB, 2024). The data used in the study were obtained at the Airport Meteorological Station, Warsaw Chopin Airport (World Meteorological Organization code 12375). The station provides comprehensive data regarding the climate and meteorological conditions in Warsaw due to the high intensity of air traffic, the list of measured parameters available in this database is provided in Tab. 1. In the study all parameters were used.

In Poland, air quality monitoring is carried out by the Chief Inspectorate for Environmental Protection (GIOŚ) through a network of reference stations, which form the foundation of the atmospheric assessment system. These stations are equipped with approved analysers, enabling continuous and precise measurements of concentrations of air pollutants. In Warsaw there are 5 stations measuring PM_{10} concentrations, whose locations are provided in Fig. 2. The brief summary of data used in the study for each air quality stations is provided in Tab. 2 while the monthly average concentrations are for each station are provided in Fig. 1.

It is noteworthy that all sites demonstrate a marked increase in PM_{10} levels in March, which may be indicative of a transient event or phenomenon, such

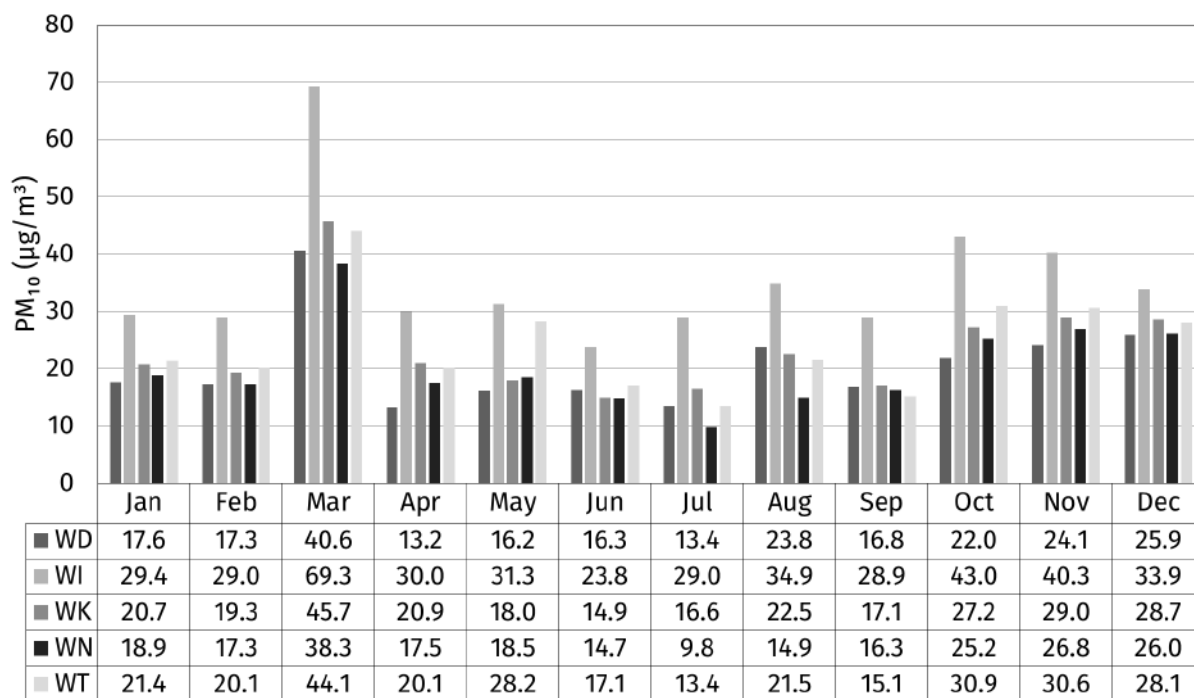


Figure 1.

The monthly average concentration of PM₁₀ at five air quality stations in Warsaw in 2022

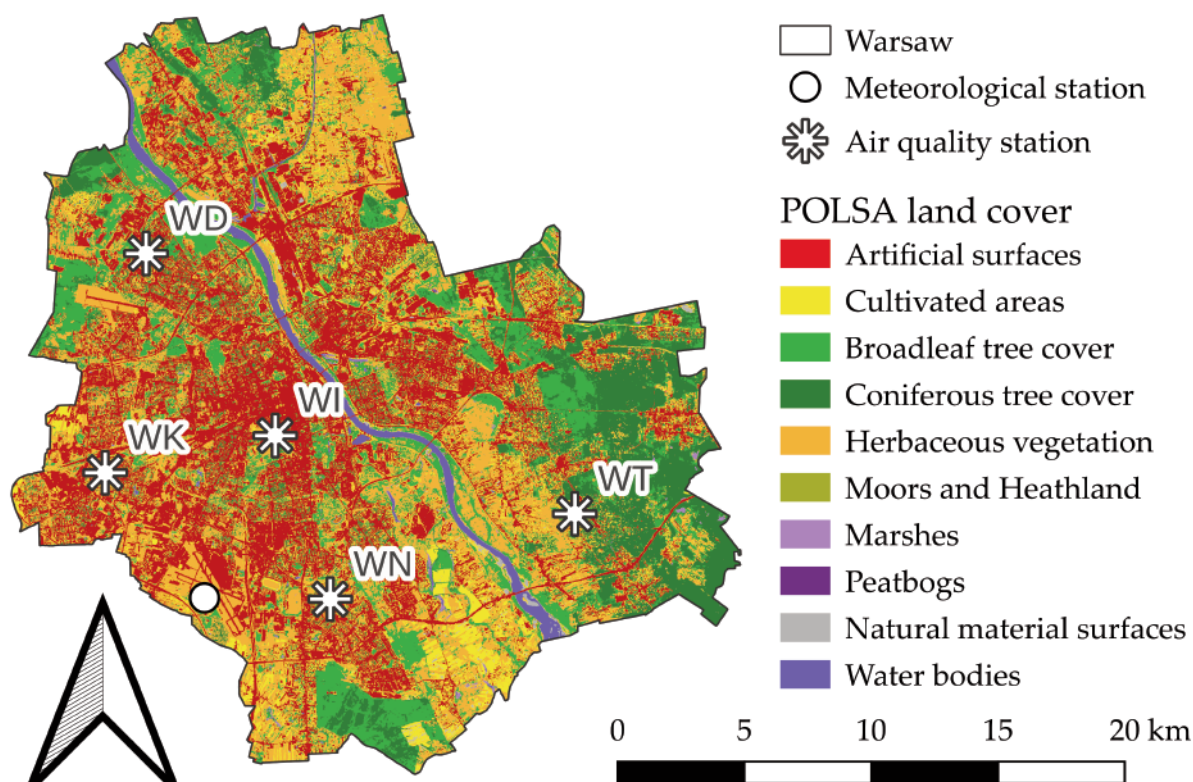


Figure 2

Location of meteorological station, air quality stations (GIOŚ, 2023) on the background of land cover (GUGiK, 2025) within borders of Warsaw (Główny Urząd Geodezji i Kartografii, 2022) created using QGIS (QGIS Development Team, 2021)

Table 1.**List of available meteorological parameters at Warsaw-Okęcie (Warsaw Chopin Airport Meteorological Station, WMO 12375)**

Parameter name	Unit	Parameter name	Unit
Daily maximum temperature	(°C)	Sunshine duration	(hours)
Daily minimum temperature	(°C)	Duration of rain	(hours)
Daily average temperature	(°C)	Duration of snow	(hours)
Minimum ground temperature	(°C)	Duration of rain and snow	(hours)
Daily total precipitation	(mm)	Duration of hail	(hours)
Precipitation type	(S/W/)	Duration of fog	(hours)
Snow depth	(cm)	Duration of mist	(hours)
Snow water equivalent	(mm/cm)	Duration of rime	(hours)
Occurrence of snow cover	(0/1)	Duration of glaze	(hours)
Occurrence of lightning	(0/1)	Duration of low-level snow drift	(hours)
Ground state	(Z/R)	Duration of high-level snow drift	(hours)
Lower isotherm	(cm)	Duration of turbidity	(hours)
Upper isotherm	(cm)	Duration of wind $\geq 10\text{m/s}$	(hours)
Actinometry	(J/cm ²)	Duration of wind $> 15\text{m/s}$	(hours)
		Duration of thunderstorm	(hours)
		Duration of dew	(hours)
		Duration of hoar frost	(hours)

Table 2.**Air monitoring stations located in Warsaw, Poland with basic statistics. The data from these points were used from the model in this study. Data in table are based on (GIOŚ, 2025)**

Symbol on map	International code	PM ₁₀ 24-hour averages yearly coverage (%)	Minimum daily concentration (µg/m ³)	Maximum daily concentration (µg/m ³)	Mean concentration (µg/m ³)	C _{90.5} (µg/m ³)	WGS84 coordinates
WD	PL0308A	93.4	4.0	75.7	20.8	36.3	52.285073°N 20.933018°E
WI	PL0140A	99.7	6.8	184.5	35.3	59.0	52.219298°N 21.004724°E
WK	PL0739A	95.6	3.2	86.5	23.6	41.6	52.207742°N 20.906073°E
WN	PL0141A	97.0	2.8	69.6	20.4	36.2	52.160772°N 21.033819°E
WT	PL0717A	96.4	5.9	79.5	24.4	43.1	52.188474°N 21.176233°E

as dust intrusion or increased urban activities. This is followed by a significant decrease in PM₁₀ levels during the subsequent spring months. In contrast, winter levels remain moderate but tend to increase slightly in December, potentially reflecting increased heating emissions amid stagnant air conditions. Summer months generally exhibit lower PM₁₀ concentrations, particularly in July, likely due to enhanced atmospheric dispersion, although some areas register an increase in August. Finally, autumn is characterised by a gradual rise in PM₁₀ levels, reflecting the influence of reduced dispersion and possibly intensified residential emissions as temperatures drop. Seasonal variations in meteorological conditions, including temperature, precipitation, and wind patterns, have been demonstrated to exert a substantial influence on the concentrations of particulate matter (PM₁₀) in

urban environments (Rogula-Kozłowska et al., 2014; Sówka et al., 2018). For instance, during the colder months (e.g., January, February, and December), increased heating demands and reduced dispersion of pollutants have been shown to result in elevated PM₁₀ levels, as evidenced by the elevated concentrations observed in Fig. 1. Conversely, the warmer months (e.g., June, July, and August) may experience lower PM₁₀ concentrations due to increased atmospheric mixing and precipitation, which can effectively remove particulates from the air.

2.3. Land cover data

The Polish Space Agency (POLSA), on demand of Poland's Head Office of Geodesy and Cartography, has developed the POLSA land cover (POLSA LC)

data set. This detailed 10-meter-by-10-meter raster, delineated in the ETRF2000-PL/CS92 coordinate system (EPSG: 2180), encompasses the entirety of Poland's territory, meticulously partitioned into 71,520 columns and 69,759 rows (GUGiK, 2025; POLSA, 2022). The land cover is determined through an automated classification process using multi-temporal Sentinel-2 imagery, random forest classifiers, and the S2GLC PL2020 methodology (Malinowski et al., 2020). A notable feature of the POLSA LC data is its yearly updates, with land cover information available for 2019, 2020, and 2021. This high temporal resolution facilitates the identification of rapid land cover changes, forest and water body/wetland area modifications, and the assessment of expanding anthropogenic zones that increase surface runoff.

The generation of POLSA LC data entails the classification of multi-temporal Sentinel-2 satellite images from the growing season (April to mid-October) with a cloud cover limit of 50%. The process entails the selection of 10 to 20 images per scene, distributed uniformly throughout the growing season, and the implementation of atmospheric correction using the Sen2Cor algorithm prior to classification by the Random Forest method (POLSA, 2024). The resulting classification data undergoes validation using a minimum of 15% of scenes within Poland's borders and a minimum of 30% of the total area analysed. A minimum of 10,000 samples are utilized in both the semantic and geometric layers of the map, ensuring an overall accuracy of at least 80% and 70% for individual classes, respectively. The land cover maps for the years 2019-2023 are accessible on the Portal, displaying the original 10-meter spatial resolution of the source imagery, categorized into 10 classes: Artificial surfaces, Cultivated areas, Broadleaf tree cover, Coniferous tree cover, Herbaceous vegetation, Moors and Heathland, Marshes, Peatbogs, Natural material surfaces, and Water bodies. The land cover of Warsaw is provided in Fig. 2 while the land cover in 1-km from air quality stations is provided in Tab. 3.

2.4. The procedure and software

The analyses provided in this study were based on the two main programs QGIS (QGIS Development Team, 2021) and Gretl (GRETl, 2024). Spatial analyses were performed in QGIS. Firstly the data about the land cover in study area was extracted to from the WCS service provided by Head Office of Geodesy and Cartography (GUGiK, 2025) to the local raster file. The locations of air quality stations were obtained from Chief Inspectorate for Environmental Protection (GIOŚ, 2023) while location of meteorological station was determined by satellite images of Warsaw Chopin Airport (GUGiK, 2022). For the layer containing air quality stations' locations a zonal histogram was performed in QGIS attributing to each location the area of given land cover withing 1 km from the station. Hence, the land cover structure was assigned to each location, constant through the year. The air quality data were 5 timeseries of 365 days. The timeseries were stacked into one table creating 1825 rows table. The table was joined on the location with landcover structure table to each location a land cover structure was assigned.

3. RESULTS AND DISCUSSION

3.1. PM₁₀ concentration model

The model for explaining the variability of PM₁₀ was developed based on meteorological and land cover data. Initially, the model was developed for all independent variables, i.e. parameters mentioned in Tab. 1 and Tab. 3. First, collinear and constant variables were excluded from the subsequent analysis. The GRETl software provided the statistical significance of all coefficients of the linear model. The next step was to drop variables with high p values, i.e. greater than 0.05. The parameters of the obtained model are provided in Tab. 4. The model was subjected to testing for the exclusion of “duration of fog” and “duration of wind >10 m/s”, as these parameters

Table 3.

Land cover structure in 1-km buffer from air quality stations in Warsaw. The types of land cover with area smaller than 0.01 ha (no pixels in raster) were removed from the table

Area [ha]	Artificial surfaces	Cultivated areas	Broadleaf tree cover	Coniferous tree cover	Herbaceous vegetation	Moors and Heathland	Peatbogs	Natural material surfaces	Water bodies
WI	192.01	21.55	31.80	11.99	56.17	0.37	0.05	0.01	0.48
WN	149.49	45.19	19.83	23.09	75.06	0.96	0.30	0.00	0.48
WD	159.26	20.23	51.94	29.74	51.72	0.68	0.32	0.08	0.48
WK	166.21	22.91	14.56	21.16	85.74	2.23	0.16	0.90	0.48
WT	14.85	54.74	35.19	116.06	56.62	2.50	0.00	0.00	0.48

Table 4.
Parameters of the linear model of PM₁₀ concentration based on meteorological conditions and surrounding land cover. The significance of coefficients is denoted with asterisk codes, the coefficients with significance $p < 0.0001$ are denoted with ****, $p < 0.001$ with ***, $p < 0.01$ with **, and $p < 0.05$ with *. The standard error values are provided up to two significant figures while the value of coefficient with the agreement of decimal places as standard error

Parameter (unit of coefficient)	Coefficient	Standard error
Daily maximum temperature ($\mu\text{g}/\text{m}^3\cdot^\circ\text{C}$)	1.321****	0.076
Daily minimum temperature ($\mu\text{g}/\text{m}^3\cdot^\circ\text{C}$)	-1.894****	0.095
Duration of rain ($\mu\text{g}/\text{m}^3\cdot\text{h}$)	-0.695****	0.092
Duration of snow ($\mu\text{g}/\text{m}^3\cdot\text{h}$)	-1.08****	0.14
Duration of fog ($\mu\text{g}/\text{m}^3\cdot\text{h}$)	0.55**	0.25
Duration of mist ($\mu\text{g}/\text{m}^3\cdot\text{h}$)	0.940****	0.059
Duration of wind $\geq 10\text{m/s}$ ($\mu\text{g}/\text{m}^3\cdot\text{h}$)	-0.59**	0.23
Duration of hoar frost ($\mu\text{g}/\text{m}^3\cdot\text{h}$)	1.04****	0.17
Artificial surfaces area ($\mu\text{g}/\text{m}^3\cdot\text{ha}$)	0.420****	0.019
Broadleaf tree cover ($\mu\text{g}/\text{m}^3\cdot\text{ha}$)	-0.754****	0.046
Coniferous tree cover ($\mu\text{g}/\text{m}^3\cdot\text{ha}$)	0.637****	0.030
Herbaceous vegetation ($\mu\text{g}/\text{m}^3\cdot\text{ha}$)	-0.681****	0.038

showed the lowest statistical significance. However, the elimination of these parameters from the model resulted in an increase in both the Akaike Information Criterion and the Bayesian Information Criterion, as well as a decrease in the R^2 value. The R^2 value of the model presented in Tab. 4 is 0.850.

3.2. Meteorological parameters coefficients

As this is a simple linear model, the interpretation of the coefficients' values is straightforward. The coefficient with maximum daily temperature is $1.321 \pm 0.076 \mu\text{g}/\text{m}^3\cdot^\circ\text{C}$. It has thus been suggested that elevated temperatures may have a significant impact on the release and later lift of dust particles into the atmosphere. Maximum diurnal temperatures have been shown to have a considerable effect on PM₁₀ atmospheric concentrations, due to a number of complex physical and chemical processes. This observation is in agreement with previous works (Al-Hemoud et al., 2021). The following mechanisms can be plausible causes of increased concentrations of this particular pollutant in response to higher temperatures:

Surface drying and dust uplift. Elevated temperatures have been shown to cause moisture to evaporate rapidly from surfaces such as roads, fields and other areas. This phenomenon leads to an increased propensity for dust particles to be released into the atmosphere. The creation of dry conditions has been shown to result in an enhancement of dust particles

present in the atmosphere, a phenomenon that is particularly evident in rural and urban areas with high traffic density. The presence of additional factors, such as construction or other types of human activity, can lead to a substantial increase in dust concentrations (Bukowski & Van Den Heever, 2022; Garcia-Carreras et al., 2021; Kim et al., 2013; Qi et al., 2023; Raupach & Lu, 2004).

Thermal inversion. It occurs when a warmer layer of air is positioned above a colder layer in close proximity to the ground. This results in the entrapment of pollutants, including PM₁₀, within the lower atmospheric layer due to their inability to rise and disperse. Such conditions are more prevalent in the early morning or late evening hours on warmer days. Cumulative pollution leads to localized increases in PM₁₀ concentrations, which can result in significant health concerns, particularly in densely populated areas (Lagmiri & Dahech, 2024; Nejad et al., 2023; Staehle et al., 2022; Yavuz, 2024).

Chemical reactions favouring the formation of secondary particulate matter. Secondary particulate matter is formed through chemical reactions that are favoured by higher temperatures. Nitrogen oxides and ammonia, which are by-products of various industrial and transport processes, react with heat and solar radiation to form secondary PM₁₀ particles. This process has the potential to increase the overall concentration of particulate matter in the air, and to alter the chemical composition of PM₁₀, which can have additional health consequences as different types of particles have different toxic properties (Deng et al., 2021; Thomsen et al., 2024).

Increased human activity at higher temperatures. Warmer days are often conducive to increased industrial and construction activity and an increase in traffic. This results in higher emissions of PM₁₀ particles, which are released into the atmosphere from various sources. In urban areas, where the concentration of industrial activity and traffic is high, elevated temperatures can precipitate severe smog and air pollution, engendering health risks for residents, particularly those afflicted with respiratory diseases (US EPA, 1995).

A 1°C higher minimum temperature results in a decrease in PM₁₀ concentrations of approximately $1.894 \pm 0.095 \mu\text{g}/\text{m}^3$. This may mean that warmer nights may favour lower atmospheric dust concentrations.

Lower emissions from local sources. On warmer nights, especially in cities, there may be less traffic

and industrial activity. Reduced transport activity and smaller industrial operations lead to lower atmospheric dust emissions. The combination of reduced generation of pollutants and enhanced dispersion can lead to a decline in PM_{10} concentrations. During warmer periods, particularly when temperatures do not decline significantly, residents can opt to reduce the use of heating appliances. This reduced burning leads to a decrease in emissions into the atmosphere (Jandacka et al., 2024; Salva et al., 2023; Senyel Kurkcuoglu & Zengin, 2021).

The urban heat island effect. In urbanized areas, higher night-time temperatures may be a result of the heat island effect, where cities retain heat more effectively than surrounding rural areas. This effect can lead to better air mixing, which in turn can promote a reduction in pollutant concentrations (Rao, 2014; Wang et al., 2022; G. Yang et al., 2021).

Rainfall has been shown to have a significant impact on air quality, with each hour of rainfall resulting in a decrease of $0.695 \pm 0.092 \mu\text{g}/\text{m}^3\cdot\text{h}$ in the 24-hour average PM_{10} concentrations. This phenomenon can be attributed to the action of rainfall, which serves as an air purification mechanism by removing particulate matter from the atmosphere. It has been demonstrated that each hour of snowfall leads to a decrease in PM_{10} concentrations of approximately $1.08 \pm 0.14 \mu\text{g}/\text{m}^3$. In a manner analogous to rain, snow also contributes to the removal of pollutants from the air. The duration of snowfall exerts a significant impact on atmospheric PM_{10} concentrations, with numerous benefits for air quality. The following are some of the key phenomena through which prolonged snowfall reduces particulate concentrations: Rainfall and snowfall exerts a substantial influence on air quality. Prolonged rainfall is effective in removing PM_{10} particles from the atmosphere. Raindrops collect particles from the air and transport them to the ground, a process known as “pollution flushing”. This leads to a significant reduction in the concentration of particulate matter in the air. Rainfall increases the humidity of the air, which promotes the agglomeration of dust particles. High humidity causes dust particles to combine with water to form larger aggregates that fall to the ground. High atmospheric humidity can lead to increased condensation of particles, which results in them becoming heavier and falling to the ground, thus reducing their concentration in the air. During rainfall, traffic and other activities that can generate PM_{10} , such as construction or industrial work, are

often reduced, thereby leading to a decrease in the amount of particulate matter emitted into the atmosphere. Longer rainfall events, especially those of moderate intensity, are more effective in removing pollutants from the air because their effects persist over a longer period of time. Repeated rain cycles can lead to a continuous reduction in PM_{10} concentrations. (Maboa et al., 2022; Olszowski, 2016; Widziewicz et al., 2017; Zhou et al., 2020).

The duration of haze has been shown to have a significant impact on PM_{10} concentrations, with an increase of approximately $0.55 \pm 0.25 \mu\text{g}/\text{m}^3$ observed for every hour of haze. The accumulation of dust is promoted by fog in the lower layers of the atmosphere, leading to an increase in PM_{10} concentrations of around $0.940 \pm 0.059 \mu\text{g}/\text{m}^3$ over a longer period of haze. Haze and fog have been found to cause dust to settle in the atmosphere. The duration of fog/haze has a significant impact on air quality, and its effects on PM_{10} concentrations can be understood in conjunction with visibility. Moreover, Fog often accompanies calm atmospheric conditions, limiting natural air movement. Low wind speeds make pollutants, including PM_{10} , less likely to disperse, leading to their accumulation in the lower layers of the atmosphere (Majewski et al., 2021, 2024; Maurer et al., 2019; Won et al., 2020).

The decline in PM_{10} concentrations of approximately $0.59 \pm 0.23 \mu\text{g}/\text{m}^3$ for each hour of wind speeds $\geq 10 \text{ m/s}$ can be attributed to several key phenomena associated with the effects of intense winds. These winds contribute to the dispersion of PM_{10} particles in the atmosphere. Due to the high air velocity, the particles are lifted and transported over greater distances, causing the dust concentration in a given area to decrease. The particles are aerated and dispersed, and in the case of strong winds, dust particles can be transported to areas where their concentration is lower (Chalvatzaki et al., 2012; Yang et al., 2024).

3.3. Land cover parameters coefficients

3.3.1. Artificial surfaces

The coefficient value for area of artificial surfaces indicates that an increase in area by 1 ha (10000 m^2) results in a PM_{10} concentration increase of approximately $0.420 \pm 0.019 \mu\text{g}/\text{m}^3$. The real uncertainty of the coefficient is higher due to the uncertainty in determination of land cover, that can be elaborated with (Białowicz et al., 2024). The increase in atmospheric concentrations of PM_{10} due to anthropogenic

emissions is the result of a number of complex processes and mechanisms.

Anthropogenic surfaces have been demonstrated to be a contributing factor to an increase in PM_{10} concentrations. These areas include roads. The combustion of fuels in car engines directly emits PM_{10} (Klejnowski et al., 2013). Secondly, the abrasion of tyres, brakes and road surfaces releases additional particles into the air (Rybak et al., 2020). Thirdly, the lifting of dust from roads and car parks due to vehicle traffic also contributes to the problem.

Furthermore, emissions from the combustion of solid fuels, such as coal or wood, in domestic cookers and boilers, contribute to the emission of PM_{10} particles (Badyda et al., 2020; Edwards et al., 2014). Additionally, the emissions from chimneys of single-family houses, especially during the heating season, serve to further increase the concentrations of these pollutants (Martins & Carrilho Da Graça, 2023). The manufacturing processes, fuel combustion, and the transportation of raw materials and products in industrial plants have also been identified as significant sources of PM_{10} particles. Finally, landfills, bulk material piles, and construction sites have been found to be potential sources of secondary dust (Chalvatzaki et al., 2010, 2012).

Construction activities, such as demolition, digging, and transport of materials, release substantial amounts of PM_{10} into the atmosphere, and renovation and retrofitting work in urban areas also contributes to the concentration of these pollutants (Azarmi & Kumar, 2016; Brown et al., 2015).

3.3.2. Tree cover

The analysis indicates that deciduous forests exhibit enhanced efficacy in trapping PM_{10} , although both forest types contribute to the reduction of air pollution. The coefficient for deciduous forests is -0.754 , signifying that an increase of 1 ha in the area under consideration results in a decline of $0.754 \pm 0.046 \mu\text{g}/\text{m}^3$ in PM_{10} concentrations. Conversely, for coniferous forests, the value of the coefficient is 0.637 , indicating that an increase in area by 1 ha is associated with an increase in PM_{10} concentration of $0.637 \pm 0.038 \mu\text{g}/\text{m}^3$. The uncertainty of these coefficients is underestimated due to accuracy of land cover (Białowicz et al., 2024).

In deciduous forests, the annual process of leaf shedding ensures that the PM_{10} particles that accumulate on the leaves are removed from the plants along with

the falling leaves, helping to reduce pollutant levels in the air (Marando et al., 2016). Conversely, coniferous trees, which retain their needles throughout the year, retain dust for longer, which can encourage dust to rise back into the atmosphere during dry periods (Pace & Grote, 2020).

Deciduous trees possess leaves with greater absorption capacity than needles (Popek et al., 2017) and higher levels of porosity, enabling them to more effectively capture and retain not only dust but also other pollutants, including sulphur and nitrogen compounds (Trees Improve Air Quality | Edmond, OK - Official Website, n.d.).

Coniferous trees have more waxy needles, which reduces their ability to capture particulate pollutants, although they are better at trapping gases. Coniferous trees, such as pines and spruces, emit volatile organic compounds (VOCs) (Kivimäenpää et al., 2022), primarily terpenes (Celedon & Bohlmann, 2019), which function as precursors to air pollutants. In the atmosphere, terpenes react with ozone and nitrogen oxides, resulting in the formation of secondary organic aerosols (SOAs) (Maison et al., 2024). These fine particles have an impact on air quality, particularly on hot days, when the intensification of chemical reactions promotes the formation of particulate matter, thereby increasing overall air pollution levels (Churkina et al., 2017; Ghirardo et al., 2020; Gu et al., 2021).

The preservation and expansion of deciduous forests in urban and suburban areas is recommended, given their proven capacity to reduce PM_{10} levels. Targeted planting programmes, reforestation initiatives, and green buffer zones with deciduous species could be integral components of strategies to mitigate particulate pollution. Moreover, caution should be exercised with the expansion of coniferous forests in contexts where PM_{10} accumulation is a concern, as their characteristics may inadvertently contribute to higher pollutant concentrations, particularly during dry periods. It is recommended that adjustments to land-use planning and vegetation management practices be informed by these insights, with a view to achieving more effective and sustainable air quality improvements.

3.3.3. Herbaceous vegetation

Herbaceous plants, such as grasses and other low-growing vegetation, possess leaves and stems that function as natural filters. When PM_{10} particles become airborne, they have the capacity to settle on

the surfaces of these plants. The leaves of the plants act as a trap for these particles, thereby reducing their concentration in the air. In addition to this function, plants have the ability to attract certain chemical pollutants, including heavy metals and other toxic substances that may be present in PM₁₀ particles. Through a combination of biological and chemical processes, plants can reduce the concentrations of these pollutants (Gao et al., 2015; Marando et al., 2016; Thao et al., 2014).

Herbaceous vegetation plays a pivotal role in stabilising the soil through its root system, thereby mitigating the risk of erosion. This process not only reduces the amount of dust in the atmosphere but also mitigates its uplift, particularly in regions where soil is susceptible to wind exposure. This phenomenon assumes particular significance in rural areas, where the presence of crops can serve to reduce the concentration of dust particles in the atmosphere (C. Yang et al., 2020; Y. Yang et al., 2024).

Urban greening initiatives are defined as the establishment of green corridors, roadside plantings, and community gardens that prioritise herbaceous plants, particularly in areas prone to high dust exposure or soil erosion. Such measures have been shown to help capture and reduce airborne particulate matter (Janhäll, 2015), whilst also mitigating soil erosion and dust uplift in rural and peri-urban areas. Integrating these strategies into land use and urban planning policies could significantly enhance natural pollutant removal, contributing to healthier, more sustainable environments (Kabisch et al., 2016).

4. CONCLUSIONS

This study enhanced traditional PM₁₀ modelling that used meteorological parameters by incorporating land cover variables, thereby demonstrating the value of a more integrated approach. The model demonstrated the significant influence of environmental conditions and land cover types on PM₁₀ concentrations. Meteorological factors, including temperature, fog, mist, and frost, were found to be associated with increased PM₁₀ levels, while rainfall, snowfall, and intense winds were observed to have a reducing effect. The incorporation of land cover data revealed a positive correlation between PM₁₀ levels and artificial surfaces and coniferous tree cover, while the presence of broadleaf trees and herbaceous vegetation was found to mitigate pollution through dust stabilization and particle capture. This integration significantly

improved the model's accuracy, underscoring the importance of spatial variables in air quality studies.

In terms of specific air quality policy applications, these findings offer a valuable evidence base for urban planning decisions. Municipalities can use these insights to develop zoning regulations that strategically manage land use – for instance, limiting the expansion of impermeable, artificial surfaces in pollution-sensitive areas while promoting urban greening initiatives that emphasize the planting of broadleaf trees and the maintenance of herbaceous cover. Such policies could include establishing green buffers around major roads or industrial zones, incentivizing green roofs, and integrating urban forestry programs to directly target improvements in air quality. Furthermore, land cover information can inform site-specific interventions, identifying neighbourhoods that would benefit most from enhanced vegetation cover, thereby prioritizing resource allocation for greening projects.

The model in question demonstrates a strong relationship between land cover and air quality, as evidenced by its high R² value. However, it is crucial to recognize that the model is built on observed, naturally occurring data rather than on scenarios of deliberate intervention. In other words, if we begin to actively modify land cover – such as increasing deciduous forest areas while reducing anthropogenic surfaces – the new inputs would diverge from the “self-organized” conditions that the model was originally based on. This means that the anticipated benefits, like a reduction in PM₁₀ concentrations, might not be as pronounced as the model suggests, since it reflects a dynamic system under natural development rather than a system under controlled, targeted management.

The integration of satellite-derived land cover data with meteorological observations has yielded valuable insights for urban planning and air quality management, underscoring the pivotal role of vegetation and urban design in mitigating PM₁₀ pollution.

The study's findings are encouraging and pave the way for further refinement and expansion, including the application of generalized linear models (GLMs) to more accurately capture non-linear relationships and enhance predictive capabilities. The approach demonstrates considerable potential for broader implementation in the field of urban air quality management and the integration of land cover parameters into air pollution modelling sets the stage for evidence-based interventions that protect public health and promote sustainable urban environments.

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