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Original scientific paper

EVALUATING THE EFFECTIVENESS OF METEOROLOGICAL MEASUREMENTS IN ASSESSING AIR POLLUTION IN THE REPUBLIC OF NORTH MACEDONIA

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A b s t r a c t: This study examines the effectiveness of meteorological measurements in assessing air pollution in the Republic of North Macedonia. The study is based on measurements of air pollutants such as particulate matter (PM), carbon monoxide (CO) and nitrogen dioxide (NO_2). Meteorological measurements, such as temperature, wind speed, and precipitation, have been used in the past to measure air pollution levels. However, the accuracy of these measurements has not been extensively studied. The current research investigates the accuracy of meteorological measurements in assessing air pollution in North Macedonia by analyzing both long-term and short-term air quality data. The results of this study will provide insight into the reliability of meteorological measurements in assessing air pollution, and the potential for using these measurements to better understand the air quality in North Macedonia.

Key words: particulate matter; air quality; meteorological measurements; air pollution

АНАЛИЗА НА ВЛИЈАНИЕТО НА МЕТЕОРОЛОШКИТЕ ФАКТОРИ ВРЗ ЗАГАДУВАЊЕТО НА ВОЗДУХОТ ВО РЕПУБЛИКА СЕВЕРНА МАКЕДОНИЈА

А п с т р а к т: Во трудот се анализира влијанието на метеоролошките фактори врз загадувањето на воздухот во Република Северна Македонија. Во овие истражувања се мерени нивоата на загадувачите на воздух како што се цврстите честички (PM), јаглеродниот моноксид (CO) и азотниот диоксид (NO_2). При анализите се земени предвид и влијанијата на метеоролошките фактори како што се температурата, брзината на ветерот, дождовите, кои отсекогаш се користат како параметри за мерење на нивото на загадување на воздухот. Во овој труд преку статистичка анализа на податоците за квалитетот на воздухот е направена процена колку овие параметри влијаат врз квалитетот на воздухот. Резултатите од ова истражување можат да се применат како влезни параметри на доверливоста на метеоролошките мерења за процена на загадувањето на воздухот и како потенцијал за користење на овие мерења за подобра анализа на квалитетот на воздухот во Северна Македонија.

Клучни зборови: цврсти честички; квалитет на воздух; метеоролошки фактори; загадување на воздух

1. INTRODUCTION

Air pollution is one of the most severe environmental risks to human health. In cities, primary air pollutants include particulate matter (PM), sulphur dioxide (SO_2), carbon monoxide (CO), ozone (O_3), nitrogen oxides (NO_X), and volatile organic compounds (VOCs) [1]. Studies conducted by [2] and [3] demonstrate that increased levels of air pollution (including O_3, PM and SO_2) are linked to increased mortality rates. According to the report from the European Environment Agency [4], air pollution is a major cause of death in many European countries, resulting in more than 400,000 premature deaths. In addition, these pollutants can damage monuments and artwork, particularly those located in city centers [5].

Meteorological studies can be used to assess the impact of air pollution on the atmosphere, measuring the levels of air pollutants and how they affect air quality, temperature, humidity, visibility and wind speed. Similarly, green infrastructure studies can be used to assess the impact of air pollution on land use and the environment, analyzing how air pollutants affect soil, vegetation, and water resources. Common sources of air pollution include burning of fossil fuels, industrial processes, agricultural activities, and transportation, releasing pollutants such as carbon dioxide, sulfur dioxide, nitrogen dioxide, particulate matter, and volatile organic compounds into the air. These pollutants have the potential to alter local weather patterns, reduce visibility, and cause acid rain, as well as contribute to the formation of smog, which can lead to respiratory problems in people

Air pollution is especially high in urban environments due to global urbanization and the construction of new buildings in major cities, which leads to an increase in temperature and consequently, an increase in air pollution [6, 7]. This phenomenon, known as the urban heat island (UHI) effect, has been explored by many authors. According [8], city temperatures can rise by 2°C to 8°C, while newer research [9] suggests a temperature increase of 5°C to 15°C. In the paper [10] estimates that by 2030, 61% of the world's population will live in cities, and the UHI effect will be more intense due to deforestation and global warming. In order to address urban environmental problems, some authors have studied the effects of vegetation, particularly trees, on cooling urban air, shading buildings, and absorbing gaseous air contaminants [11, 12]. An innovative approach to mitigating air pollution is the implementation of green walls, green facades, and green buildings. The effectiveness of this approach has been confirmed in various cases applied in Switzerland, Sweden, UK, USA, and Spain [13]. The benefits of implementing vertical green walls and green roof surfaces on building facades include improved thermal characteristics of the objects, reduced noise levels, and reduced energy requirements for the facilities [14]. The impact of vegetation on the thermal environment of buildings was examined in the studies of [15] and [16]. In [17], it was quantified that by using green roofs in Tokyo the average ambient temperature can be lowered by 0.3°C, while [18] estimated a temperature reduction of 0.1°C. In [11], experiments were conducted to measure the influence of tree planting and re-roofing on ambient temperatures and air pollution, which concluded that the ambient temperature can be reduced by up to 3°C, and the air around the building can be cooled through the implementation of trees combined with cool roofs. The influence of garden roofs on air temperature mitigation was also investigated in [19], which concluded that garden roofs are more effective in reducing heat gain in summer than heat loss in winter. Air pollution mitigation by the implementation of green walls and green roofs was investigated in [20], while [21] evaluated different arrangements of trees on pollution dispersion. Finally, [22] suggested a Computational fluid dynamics (CFD) model for predicting pollutant levels and distribution, which was validated through a test case on a wind tunnel urban canyon in Belgium, using wind catchers to increase the dispersion process of air pollution removal.

For several years, the city of Skopje has been experiencing an issue with air quality [23]. This is due to its geospatial position, coupled with the worsening climate conditions in the winter months. The rapid urbanization and population growth have added to the energy demands of the city, particularly the heat demand in the period from November to April. The geographical position of Skopje, the capital of North Macedonia, in the Vardar river valley and its local weather conditions have caused the pollutants to build up in the city. Additionally, the city of Skopje stretches for more than 23 km, but it is only 9 km wide. For years, Skopje has had a bad reputation for the enormous exceeding concentration of PM in the air throughout the whole [24]. It is interesting to observe that the concentration of PM2.5 and PM10 in Skopje is much higher during the night. In [25], it was reported that the concentration of PM2.5 is 18% higher, while the concentration of PM10 is almost 20% higher during the night compared to the daytime periods. The observed problems as well as the changes caused by the COVID-19 pandemic were the major drivers for conducting the study presented in this paper.

This paper examines the effectiveness of meteorological measurements in assessing air pollution in North Macedonia. It evaluates the accuracy of the meteorological measurements, their ability to detect changes in air pollution levels, and their potential to be used as a tool for policy decisions. The paper also evaluates the various factors that influence the accuracy of the measurements, including seasonal weather patterns, topography, and other regional factors. Finally, the paper provides recommendations for the optimal use of meteorological measurements in air pollution monitoring and assessment in the region.

2. MEASUREMENT SYSTEM DESCRIPTION

The position of the sensor nodes in 2018 were located as depicted in Figure 1 (the sensor nodes are marked as magenta), while the positions of the sensor nodes in 2019 were changed (the sensor nodes are depicted in yellow). Sensor node 1 is now located close to the pedestrian pavement, while sensor node 2 is placed near a small green area, which is part of the building patio. Sensor node 3 is relatively closer to the secluded green area. The green wall structure consisting of two rows of hedera helix plants was installed in the beginning of the measurement setup and was planted during the spring period. The sensor nodes were placed on a platform, where two photovoltaic panels were already installed. The measurement results considering the impact of the green wall structure on air quality improvement was presented in [25]. In order to identify the influence of the green areas, traffic and movement of people, the different positions of the sensor nodes were chosen.

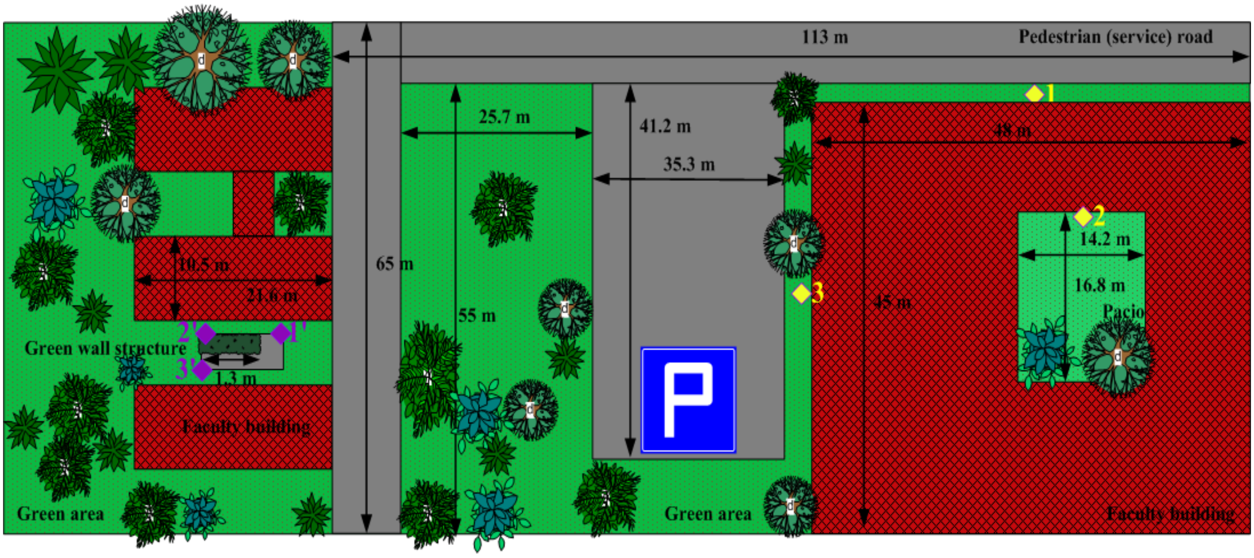


Fig. 1. Position of the sensor nodes

A wireless sensor network-based measurement system was initially developed, comprised of PM and gas sensors for monitoring air quality parameters. The monitoring system consists of a few sensor nodes, each containing four sensors and a Wi-Fi module integrated onto a single-board controller. Each node is able to measure PM2.5, PM10, CO, and NO_2 concentrations. The SDS011 is an integrated device which contains sensors for measuring PM2.5 and PM10 concentrations between 0.3 μm and 10 μm. The MiCS-4514 sensing unit also integrates two sensors, one for CO and one for NO_2 measurements. The main features of these sensing units are listed in Table 1.

The controller plays a vital role in pre-processing the data before it is sent to the network. It has a wide range of applications, from low-power sensor networks to high-power applications such as music streaming and voice encoding. The most significant features of the controller are detailed in Table 2.

The Wi-Fi modules that are integrated part of the sensor nodes, send data to the closest routers, which are located in the Faculty building. The collected data from the closest routers are uploaded on an open platform [26] and can be monitored on-line or downloaded for additional analyses.

Table 1

Main characteristics of the sensing units

	SDS011	MiCS-4514
Measurement parameters	PM2.5, PM10	CO, NO_2
Supply voltage	5 V	4.9 V – 5.1 V
Operating temperature range	–20°C –50°C	–30°C –85°C
Range	0.0 – 999.9 μg/m^3	/
CO detection range	/	1 – 1000 ppm
Sensing resistance in air	/	100 – 1500 kΩ
Maximum working current	220 mA	

Table 2

Main characteristics of the controller

	Controller
Measurement parameters	*EPS32*
Supply voltage	2.7 V – 3.6 V
Operating temperature range	–40°C –85°C
Module interface	SD Card, UART, SPI, I2C, Motor PWM
Wi-Fi frequency range	2.4 GHz – 2.5 GHz

MEASUREMENT RESULTS

The paper analyzes the pollution in Skopje in the period of May 2018 – January 2023. Due to some technical issues the data for the pollution is missing in the period of 21.09.2018 – 26.10.2018 and 19.02.2019 – 13.03.2020. The data is collected from three sensors located in the campus of the technical faculties at Ss. Cyril and Methodius University in Skopje. All of the three sensors collect data for the concentration of PM2.5, PM10, CO, and NO_2, the average values of the concentrations recorded by the three sensors for all pollutants were analyzed. The concentration of air pollutants by month are considered. The results suggest that the data for PM2.5 and PM10 is not normally distributed (Kolmogorov-Smirnov test reports p-value = 0.000), even more, the data is right-skewed with positive kurtosis. The distributions of CO and NO_2 are also not normal as Kolmogorov-Smirnov test reports p-value = 0.000. The descriptive statistics for the pollution by months is given in Tabe 3 and Table 4.

The histograms for each variable by months are given in

It is clear that the most polluted months with respect to PM2.5 and PM10 are the winter months, more precisely December and January. At the same time, the smallest concentration of PM2.5 and PM10 is reported during summer, i.e., from May to August. This is clearly evident in Figure 2a and b. If similar analysis is done for CO and NO_2, the variation is not that obvious. Still we observe that the highest concentration of CO is reported in spring (from February to April), and the lowest in June and July. When NO_2 is concerned, the lowest concentration is reported in May, and highest during winter months (Table 4 and Figure 2c and d).

Table 3

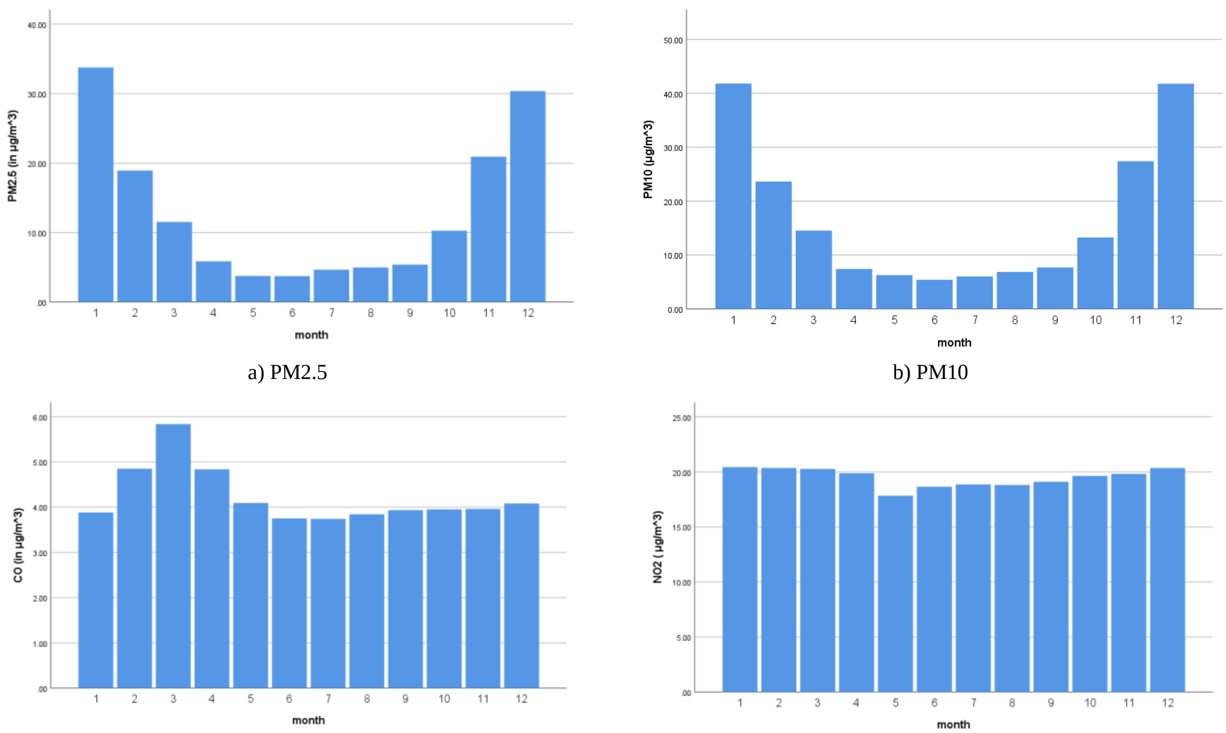
Descriptive statistics for the pollutants PM2.5 and PM10 by months in the studied period

Month	PM2.5				PM10			
	Range min	Range max	Mean	St.dev.	Range min	Range max	Mean	St.dev.
Jan.	0.6	305.9	33.7	36.8	0.7	372.0	41.8	45.3
Feb.	0.5	104.0	18.9	16.3	0.5	128.5	23.6	20.3
March	1.1	67.3	11.5	9.1	1.4	86.4	14.5	11.0
April	0.7	25.2	5.8	3.4	0.8	30.5	7.4	4.0
May	0.3	22.4	3.7	2.1	0.5	32.9	6.3	3.9
June	0.8	22.7	3.7	2.3	1.1	31.9	5.4	3.0
July	0.9	16.0	4.6	2.3	1.25	20.9	6.0	2.7
Aug.	1.3	23.0	5.0	2.1	1.7	27.1	6.8	3.0
Sep.	0.5	84.6	5.4	3.6	0.8	134.8	7.7	5.5
Oct.	0.4	87.6	10.3	8.9	0.7	107.0	13.2	10.8
Nov.	0.5	123.4	20.9	13.2	0.8	138.9	27.4	17.2
Dec.	0.8	162.4	30.3	26.6	1.2	219.2	41.8	38.3

Table 4

Descriptive statistics for the pollutants CO and NO_2 by months in the studied period

Month	CO				NO_2			
	Range		Mean	St.dev.	Range		Mean	St.dev.
	min	max			min	max		
Jan.	1.8	7.7	3.9	1.1	18.0	21.6	20.4	0.4
Feb.	2.2	11.9	4.8	1.6	18.5	21.7	20.30	0.4
March	2,9	12.9	5.8	1.7	15.9	21.2	20.2	0.4
April	3.2	9.37	4.8	0.9	18.0	21.0	19.9	0.4
May	1.5	6.6	4.1	1.0	3.1	20.3	17.8	3.7
June	1.4	6.4	3.7	1.1	5.7	20.1	18.6	1.8
July	1.4	7.0	3.7	1.3	13.9	19.8	18.8	0.5
Aug.	1.8	6.5	3.8	1.2	16.0	19.7	18.8	0.5
Sep.	2.1	6.9	3.9	0.9	17.3	20.1	19.1	0.4
Oct.	1.9	7.4	3.9	0.9	18.7	20.5	19.6	0.3
Nov.	1.9	7.9	3.9	1.3	19.0	20.8	19.8	0.3
Dec.	1.9	9.7	4.1	1.3	16.9	21.3	20.3	0.4



a) PM2.5 b) PM10

c) CO d) NO_2

Fig. 2. Average concentration of the pollutants PM2.5, PM10, CO, and NO_2 in the observed period

In order to see if these visually detected differences are statistically significant hypothesis tests were performed. Each test the null-hypothesis "There is no difference in the concentration of the pollutants (PM2.5, PM10, CO, and NO_2, respectively) between months", against the alternative hypothesis "There is a difference in the concentration of the pollutants (PM2.5, PM10, CO, and NO_2, respectively) between months". We set the significance level $\alpha = 0.05$. As the data for each of the considered pollutant is not normally distributed we perform the Kruskal-Willis [27] hypothesis test to see if the difference between the months is statistical significant. For all four pollutants the corresponding p-value is 0.000, which means that the null hypothesis H_0 is rejected. To locate the difference, we perform post hoc tests. The results of the post hoc test are presented in Table 5. Namely, in Table 5 the corresponding cell is marked if there is no significant difference between those two months. Different color is used for different pollutant(s).

Table 5

There is no statistically significant difference in the concentration of the corresponding pollutant(s) between months

PM2.5	PM10	CO	NO_2	PM2.5&10	PM&CO	All

	Jan.	Feb.	March	April	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
Jan.		NO_2				CO	CO	CO	CO		PM2.5&10	All
Feb.	NO_2		NO_2									
March		NO_2										NO_2
April								PM10	PM2.5&10			NO_2
May						PM2.5	PM10		NO_2			
June	CO				PM2.5			CO				
July	CO				PM10			NO_2				
Aug.	CO			PM10		CO	NO_2		(green)	CO	CO	CO
Sep.	CO			PM2.5&10		NO_2		(green)		CO	CO	CO
Oct.								CO	CO		CO	CO
Nov.	PM2.5&10							CO	CO	CO		(green)
Dec.	All		NO_2	NO_2				CO	CO	CO	(green)	

The correlations between air pollutants and meteorological factors for each month are displayed in Table 6. This study considers wind speed, precipitation, humidity, visibility, and temperature as its meteorological factors. It is found that the strongest correlation between PM2.5 and PM10 concentration and the wind speed is confirmed. A slightly stronger correlation between the PM concentrations and the real feel temperature, as opposed to the actual temperature, is also reported. However, very week correlations are noticed between PM concentrations and the humidity. All the correlation coefficient presented in Table 6 are statistically significant.

Table 6

Correlations between air pollutants and meteorological factors by months

	PM2.5	PM10	CO	NO_2	Humidity (%)	Precipitation (mm)	Visibility (km)	Wind speed (km/h)	Temperature (°C)
PM2.5	1	0.991	–0.202	0.211	0.280	–0.050	–0.044	–0.218	–0.408
PM10	0.991	1	–0.206	0.200	0.261	–0.061	–0.023	–0.219	–0.391
CO	–0.202	–0.206	1	0.342	–0.016	–.006	–0.032	–0.034	–0.299
NO_2	0.211	0.200	0.342	1	0.334	0.046	–0.125	–0.128	–0.539

CONCLUSION

This paper has analyzed the pollution in Skopje in the period of May 2018 to January 2023. The data was collected from three sensors located in the campus of the Faculty of Electrical Engineering and Information Technologies at Ss. Cyril and Methodius University in Skopje, North Macedonia, and the average concentrations of PM2.5, PM10, CO and NO_2 were recorded for each month. The collected data was not normally distributed, and was right-skewed with positive kurtosis. Although the data was missing for some periods due to technical issues, the results of this study are still important in understanding the air pollution levels in Skopje. In this paper, wind speed, precipitation, visibility, and temperature were examined as meteorological factors. It was found that the strongest correlation between PM2.5 and PM10 concentrations and wind speed was confirmed. Additionally, a negative correlation between the PM concentration and wind speed was verified in all three locations. There was a slightly stronger correlation between the PM concentrations and the "real feel" temperature. However, insignificant correlations were noticed between the PM concentrations and the humidity. It is important to take measures to reduce air pollution in the city in order to protect public health. It is hoped that more comprehensive data will be collected in the future to further our understanding of air pollution in this area. The findings of this paper are useful for the development of policy initiatives to reduce air pollution and improve air quality in Skopje.

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