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Chronic Health Risk Assessment of $PM_{2.5}$ in the Urban Core of Novi Sad, Serbia

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Abstract: Air pollution remains one of the leading environmental threats to public health, with fine particulate matter ($PM_{2.5}$) being a major contributor to chronic health risks. This study investigates spatial-seasonal variations in $PM_{2.5}$ concentrations and their associated health risks for pedestrians in the urban core of Novi Sad, Serbia. Low-cost sensors were deployed at seven urban locations to measure $PM_{2.5}$ levels during winter and summer. The results indicate significantly higher $PM_{2.5}$ concentrations in winter, with average values ranging from 23,11 to 43,03 µg/m³, compared to 11,06 to 17,07 µg/m³ in summer. A preliminary health risk assessment was conducted by calculating the lifetime average daily dose (*LADD*) and hazard quotient (*HQ*) for different age groups and genders. In winter, *HQ* values exceeded 3 for most age groups, indicating potential chronic health risks, while summer values were lower but still above 1 at certain locations. The highest risks were observed for males aged 30 - 59 and elderly individuals, particularly at locations influenced by mixed heating systems and traffic. These findings emphasize the need for targeted air pollution mitigation measures and improved urban air quality management strategies.

Keywords: low-cost measurements; $PM_{2.5}$; short-term campaign; summer season; winter season

1 INTRODUCTION

Air pollution is the foremost environmental risk factor affecting public health worldwide, resulting in considerable health, economic, and social costs [1]. In 2019, air pollution was the fourth leading cause of death globally, linked to nearly 6,7 million fatalities[2]. The population most exposed to polluted air primarily consists of urban dwellers in low- and middle-income countries, representing 55% of the global population [3]. In urban areas, commuting particularly results in significant exposure to air pollutants and this exposure varies based on factors such as the time of day, mode of transportation, chosen route, and fuel type [4]. Various regions and communities have frequently unevenly distributed negative effects of ambient air pollution [2]. Air pollution dispersion is determined by many parameters, primarily atmospheric stability, and wind [5].

The timing and extent of health effects vary and can depend on various characteristics of the pollutant, the duration of exposure, and the sensitivity of the receptor, which is influenced by genetic predisposition and homeostasis pathways [3, 5]. Both short-term (days to weeks) and long-term (months to years) exposure to air pollution can result in serious health consequences, ranging from temporary issues to chronic conditions [2]. Due to air pollution from particulate matter, approximately 7 million people die each year worldwide [6], resulting from the onset and progression of acute and chronic health issues [3]. The level of human exposure to harmful effects caused by $PM_{2.5}$ in ambient air depends on its emission sources, as well as on its size, surface and chemical composition [6]. The manifestation of negative health effects is influenced by individuals' age and pre-existing health conditions, predominantly affecting pedestrians with lung or cardiovascular diseases, pregnant women, newborns, children, and older adults [7]. The numerous negative health effects stemming from the physical and primarily chemical characteristics of $PM_{2.5}$ particles, along with the presence of specific components in their chemical composition, underscore the importance of the chemical characterisation of particulate matter [5].

The health risk associated with exposure to air pollution also depends on the amount of pollution that enters the body. According to the study [4], the incidence of finer particles is 20% higher in pedestrians and cyclists than bus passengers, and 2,5 times higher than car drivers if they have windows closed and air conditioning systems on [4]. Conversely, breathing rates during walking or cycling are likely to be significantly higher than those while riding in a car or bus, due to the increased level of physical activity. Public health modelling studies indicate that, in most cities, the benefits of physical activity exceed the risks associated with air pollution, particularly in the active transport context [8]. According to [9] at the global average background $PM_{2.5}$ of 22 $\mu g/m^3$, the benefits of physical activity significantly outweigh the risks associated with air pollution, even under extreme conditions of active travel. In regions where $PM_{2.5}$ reach 100 $\mu g/m^3$, the negative impacts would surpass the benefits after 1 hour and 30 minutes of cycling per day or more, than 10 hours of walking per day [8]. But the overall evidence remains limited for low and middle-income countries, sensitive subpopulations (children, elderly, pregnant women, and individuals with pre-existing conditions [10].

Among EU countries, air pollution from particulate matter, specifically $PM_{2.5}$, has reduced the average life expectancy by 8,6 months [11]. In Serbia air pollution was the 7 th leading risk factor for fatal outcomes in 2019 [2]. All of Serbia'spopulation reside in areas where $PM_{2.5}$ levels exceed the World Health Organization (WHO) guidelines of 5 $\mu g/m^3$, although 97% live in areas below the WHO's least stringent target of 35 $\mu g/m^3$. Monthly averages from 2018 to 2019 reveal a seasonal pattern, with the highest $PM_{2.5}$ levels occurring during winter, peaking in December and January [2]. The primary energy supply during winter in Serbia in 2018 was dominantly coal, followed by oil and oil products, other renewables, natural gas, and hydropower [12].

This paper aimed to provide preliminary research on health risks in different parts of the city and to emphasize health risks due to seasonal exposure patterns of pedestrians to intense emission sources of $PM_{2.5}$, particularly during winter. Citizens of Novi Sad are continuously exposed to heavily ambient air pollution during the heating season, which is reported in the findings of the Air quality plan in the "Novi Sad" agglomeration for the period 2022 - 2026. year [13]. Since locally oriented particulate pollution is common in urban environments and can be intensive, we have assessed the preliminary chronic risk of exposure to $PM_{2.5}$ based on seasonal variations in $PM_{2.5}$ levels at seven typical urban locations in Novi Sad. Exposure was assessed for different age groups (3 - 9, 10 - 17, 18 - 29, 30 - 59, and > 60 years) and both genders (male and female) of pedestrians engaged in light activities, such as walking, based on the scaled low-cost sensor (LCS) measurements in the City of Novi Sad.

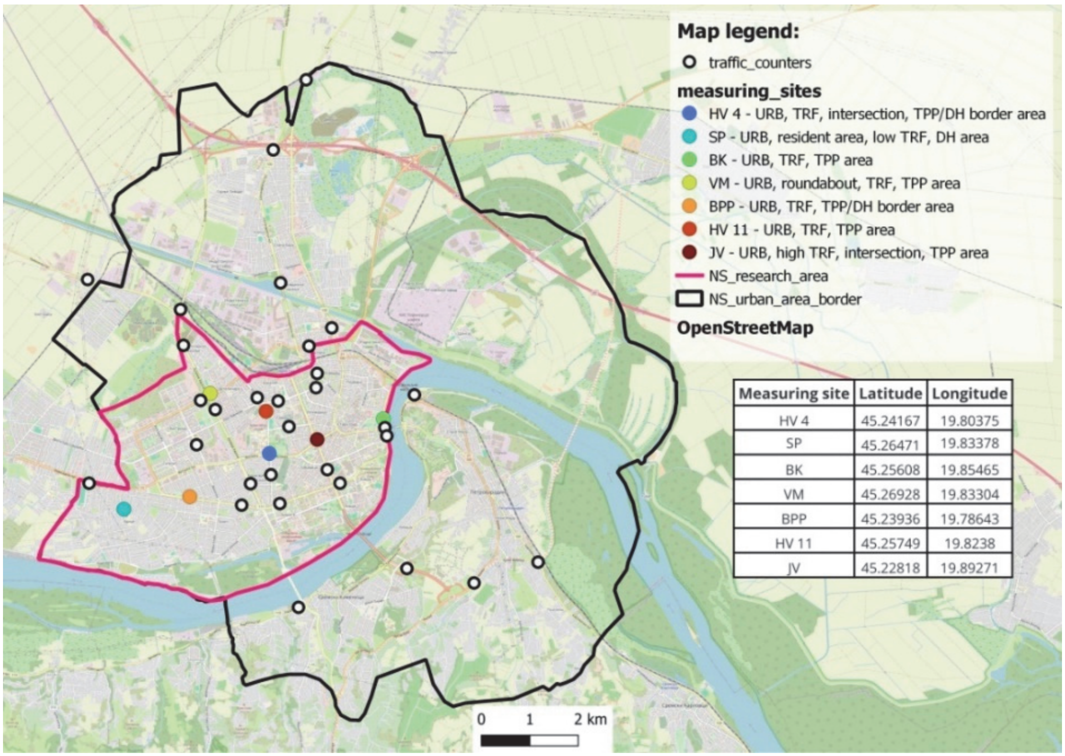
2 MATERIALS AND METHODS

2.1 Research Area Characteristics

The City of Novi Sad represents an urban-industrial agglomeration that is divided by the Danube River into two topographical regions: the northern Bačka plain and the southern Srem. It is the capital of the Autonomous Province of Vojvodina [13]. Research within this study was conducted in the region of the northern Bačka plain. The climate in Novi Sad can be characterized as a transition between moderately continental and continental, with features of subhumid and microthermal climates. This type of climate results in all four seasons, and the region is particularly marked by pronounced temperature differences throughout the year, with the abrupt transitions between the colder and warmer halves of the year.

2.2 Sampling Campaign

Particulate matter sampling was conducted in the period of winter and summer of 2020 and 2021, for 10 days on each of 7 locations. Particle concentrations were measured by low-cost devices (from ekoNET, equipped with particulate PMS7003 sensors) with temporal resolution from 1 to 3 minutes. The sensors underwent initial calibration by the manufacturer and were scaled using data from a reference measurement station under the jurisdiction of the Serbian Environmental Protection Agency (SEPA). The SEPA station is located in the street Bulevar Jaše Tomića. Measuring locations were classified as urban (URB), with different characteristics regarding heating systems depending on the season, traffic intensity (TRF), vicinity of intersections or roundabouts, with all time present pedestrians. Names of the measuring sites were also abbreviated: Hajduk Veljkova 4 (HV 4), Sopoćanska (SP), Beogradski kej (BK), Veselina Masleše (VM), Bulevar patrijarha Pavla (BPP), Hajduk Veljkova 11 (HV 11) and Jevrejska (JV). Regarding sites properties, parts of the city heated by domestic heating (DH) systems represent one area, and sites heated on the City Thermal Power Plant (TPP) represent another. The research area is shown in Fig. 1, along with the properties and coordinates of the measuring sites.



Measuring site	Latitude	Longitude
HV 4	45.24167	19.80375
SP	45.26471	19.83378
BK	45.25608	19.85465
VM	45.26928	19.83304
BPP	45.23936	19.78643
HV 11	45.25749	19.8238
JV	45.22818	19.89271

Figure 1 Research area in Novi Sad

2.3 LCS $PM_{2.5}$ Measuring Data Scaling

LCS devices were collocated with the referent SEPA station in BulevarJašeTomića Street (Fig. 2) during the summer period for 14 days, to scale the measured 24 hour $PM_{2.5}$ concentration values before they were used for health risk assessment [14].

Figure 2 LCS collocation with RF

The measured $PM_{2.5}$ concentration and scaled datasets underwent basic statistical analysis, including calculation of the average (*AVG*), standard deviation (*SD*), mean absolute error (*MAE*), and relative error (*RE*). In addition, by determining correlations between measured and scaled 24 hour concentration values, the coefficients of determination (R^2) were analysed for each of the collocated sensors in comparison to the reference SEPA station. These analyses provided a direct comparison of the scaling efficiency of sensor data, thereby offering insight into the reliability of the sensors in estimating chronic health risks during the observed seasonal periods.

2.4 Health Risk Assessment

Health risk assessment of pedestrians in the urban part of the city during the winter and summer seasons was assessed by calculating two parameters, the lifetime average daily dose for winter and summer (*LADD* win and *LADD* summ, µg/kg-day) and hazard quotient (*HQ*) for winter (*HQ* win) and summer (*HQ* summ). According to the methodology outlined in the research by [15], *LADD* win and *LADD* summ were derived based on Eq. (1):

$$LADD = \frac{Cair \cdot IR \cdot ED \cdot EF}{BW \cdot AT} \tag{1}$$

where *Cair* is the $PM_{2.5}$ concentration in the air (µg/m^3) during winter and summer sampling period, *IR* (m^3/hour) is the inhalation rate of a single individual depending on gender and age, *ED* is the duration of the exposure expressed in years, *EF* is exposure frequency (days), *BW* is the body weight of single individual depending on gender and age, and *AT* is the total averaging time (hours). *AT* is being calculated as a product of *EF* and *ED*.

Health risk evaluation during winter and summer expressed through *HQ* win and *HQ* summ was calculated following Eq. (2):

$$LHQ = \frac{LADD}{RfD} \tag{2}$$

The *HQ* represents the ratio between the calculated *LADD* and the reference dose (*RfD*). When the *HQ* value is 1,0 or lower, the risk of adverse health effects is considered negligible. Conversely, as the *HQ* increases beyond this threshold, the likelihood of harmful health outcomes rises. An *HQ* exceeding 1,0 is therefore indicative of a potential health risk, as confirmed by [16]. To estimate the preliminary *HQ* for different demographic groups based on age and gender, the reference dose (*RfD*) was calculated using Eq. (3).

$$RfD = \frac{RfC \cdot IR}{BW} \tag{3}$$

The reference concentration (*RfC*), a key environmental health metric that quantifies the safe concentration of a substance in the air, was set at 15 µg/m^3 [15]. This concentration corresponds to the daily exposure limit for $PM_{2.5}$ as recommended by the WHO, and is used to assess long-term exposure to $PM_{2.5}$ without causing harmful effects in the general population.

The exposure parameters applied for the calculation of *LADD*, *RfD*, and *HQ* during the winter and summer seasons are provided in Tab. 1.

Table 1 Exposure parameters for determination of preliminary chronic risk [16, 17]

Factor		Years				
		3 - 9	10 - 17	18 - 29	30 - 59	> 60
Inhalation rate (*IR* / m^3/h)	male	0,49	0,78	0,84	0,84	0.66
	female	0,45	0,66	0,66	0,66	0.59
Exposure duration (*ED*, (years))		3 - 9	10 - 17	18 - 29	30 - 59	60
Exposure frequency (*EF* / days/year)		90 (winter and summer)				
Body weight (*BW* / kg)	male	23	53	76	80	75
	female	23	50	62	68	67
Averaging time (*AT* / days)		Note: Calculated as *EF* × *ED*				

3 RESULTS AND DISCUSSION

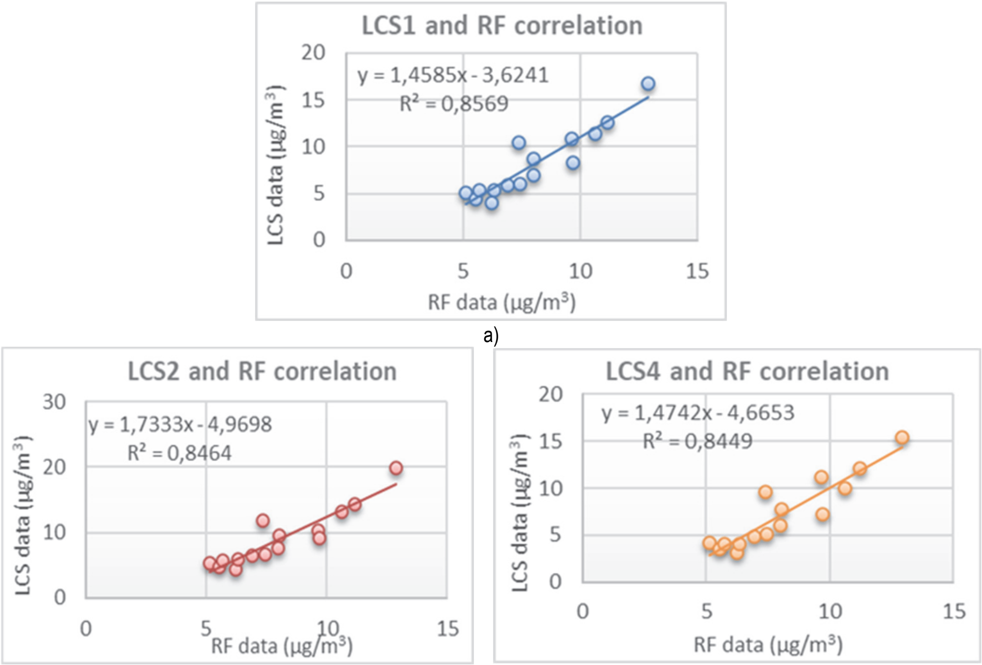
3.1 Low-cost $PM_{2.5}$ Measurements Scaling

Observations of the collocated *LCS* data with the reference station (*RF* station) provided valuable insight into certain deviations in the 24 hour measured $PM_{2.5}$ concentrations obtained by the *LCS* devices, compared to the reference station. Despite some significant discrepancies observed in the data sets, the overall concentration trends of particles during the day were quite similar. In addition to several significant deviations, there were instances where sudden changes in sensor response were noticed during the evaluation period. These included higher or lower $PM_{2.5}$ concentrations compared to the reference station's measurements. Such variations could be attributed to potential limitations in the *LCS* device's calibration or sensor sensitivity, suggesting the necessity for improved sensor calibration or adjustment for specific environmental conditions. Tab. 2 shows the values of statistical parameters, *AVG* of $PM_{2.5}$ concentrations, *SD* value, *MAE*, and *RE*, obtained during the scaling process of three *LCS* data sets

Table 2 Statistical metrics and evaluation parameters of $PM_{2.5}$ data from *RF* and *LCS*

Device and sampling frequency	*AVG* / μg/m^3	*SD* / μg/m^3	*MAE* / μg/m^3	*RE* / %
RFS 24h	8,05	2,30	-	-
*LCS*1 24h	8,12	3,63	1,38	17,00
*LCS*2 24h	8,98	4,33	1,66	18,50
*LCS*4 24h	7,20	3,69	1,79	24,30
Note: *RFS* 24h - 24 hour data from the reference station, *LCS* (1, 2 and 4) 24h - three *LCS* devices and data for 24 hour $PM_{2.5}$				

The values of *MAE* and *RE* for 24 hour measurements ranged from 1,38 to 1,79 μg/m^3 and 17 to 24,30%, respectively. The mean value and *SD* value for the *RF* station were 8,05 and 2,30 μg/m^3, respectively, while the *LCS* devices exhibited mean values in the range of 7,20 to 8,98 μg/m^3 and *SD* values between 3,63 and 4,33 μg/m^3. The coefficient of determination, R^2, calculated by analysing the 24 hour correlations of measurements from all three *LCS* with measurements from the *RF* station, ranged from 0,84 to 0,86. The presentation of the correlations in the case of 24 hour $PM_{2.5}$ measurements with three *LCS* devices and *RF* device are given in Fig. 3a to Fig. 3c.

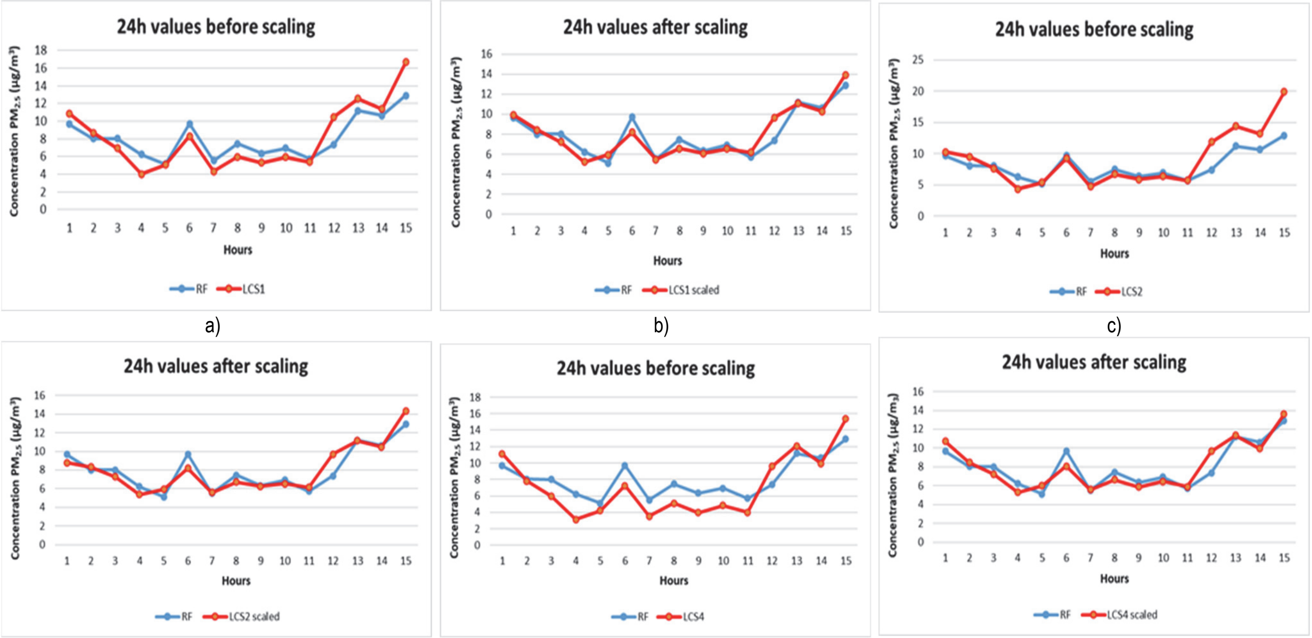


a)

b)

c)

Figure 3 Correlation of 24 hour $PM_{2.5}$ concentrations between *LCS* devices and *RF* station: a) *LCS*1 and *RF*, b) *LCS*2 and *RF*; c) *LCS*4 and *RF*



a)

b)

c)

Figure 4 Comparison of 24-hour PM2.5 concentrations measured by LCS devices and RF station before and after scaling: a - b) LCS1 i RF, c - d) LCS2 i RF; e - f) LCS4 i RF

The R2 values indicate a strong correlation between the LCS data and the data from the RF station, which implies that the LCS devices provide valuable insight into PM2.5 particle pollution trends, especially in terms of decreasing or increasing PM2.5 concentrations. However, the precision of the LCS data appeared to be relatively low, as indicated by the high *SD* values, which reflect a significant dispersion of the data points with respect to the mean. This suggests that while the LCS devices are capable of detecting trends in PM2.5 concentrations, the overall accuracy of individual measurements remains moderate, compared to the data from the RF.

The regression equations derived from the analysis, i.e. the elements of the equation (slope and intercept) were subsequently used for the process of scaling 24 hour LCS data through inverse linear regression to improve the data's accuracy [14]. The scaling process significantly enhanced the accuracy of the LCS data (as shown in Fig. 4a to Fig. 4f), reducing the error values. Before scaling, the MAE and *RE* values for the 24 hour data ranged from 1,38 to 1,79 µg/m3 and 17 to 24,3%, respectively, whereas after scaling, the *MAE* and *RE* values were reduced to the range of 0,70 to 0,77 $\mu g/m^3$ and 9 to 10%, respectively. This improvement demonstrates that the scaling process significantly increased the reliability of the LCS data, offering a more accurate representation of PM2.5 concentrations, and thus increasing the potential for using LCS devices in long-term air quality monitoring applications.

3.2 Scaled Particle Concentrations During Winter and Summer

Ambient particle pollution in Novi Sad during the winter season exhibited pronounced spatial variations among the measured locations, with significantly higher concentrations compared to the summer season trends. All measured locations shared a common characteristic: the presence of traffic with varying intensities on nearby roads (medium to high), comprising passenger cars, vans, and buses. However, the SP location was distinguished by low traffic intensity, primarily consisting of passenger cars and vans. In addition to these local traffic characteristics, two locations were influenced by DH areas. Specifically, the HV 4 location was situated at the border between TPP area and DH area, while the SP location was within a residential DH area featuring mixed heating systems. Many households in these areas utilized a combination of heating sources during the winter, including gas central heating as well as wood and coal heating. The elevated $PM_{2.5}$ concentrations in this area clearly highlight the influence of the mixed type of heating in residential zones during the winter, contributing to spatial variability and elevated pollutant levels. Since it was not possible to obtain information on the number and location of households that use services of private supply systems with natural gas, areas not included in the city TPP, were treated as mixed heating areas. In addition, there is also the fact that information on the number of households that heat with solid fuels does not exist.

Observing daily $PM_{2.5}$ values compared to established guidelines, winter 24 hour concentrations during the 10 day measurement period exceeded 15 $\mu g/m^3$, the proposed limit value by the WHO for $PM_{2.5}$ in ambient air, on most measuring locations. Locations such as JV, BK, and HV 11 recorded values above 15 $\mu g/m^3$ for the majority of the sampling period. On the other hand, at remaining locations, 24 hour concentrations exceeded the 15 $\mu g/m^3$ threshold on 6 - 9 days. These spatial patterns are visually reinforced in Tab. 3 through color-coding, where the predominance of orange and red hues (exceeding WHO limits) clearly identifies pollution hotspots - particularly at SP (peak 68,42 $\mu g/m^3$), where residential heating with solid fuels combines with urban congestion. In a striking contrast, the islands of green and yellow (≤ 15 $\mu g/m^3$) at HV 4 and BPP reveal how urban planning and heating infrastructure can maintain safer air quality levels even during winter. This visual dichotomy not only confirms the decisive role of local emission sources but also creates a compelling spatial framework for policy interventions: the immediate red zones demand urgent heating system upgrades, while transitional yellow areas might benefit most from traffic management solutions. Such spatially explicit risk mapping proves particularly valuable for addressing winter inversion episodes, when atmospheric conditions amplify the health impacts of these emission sources.

Table 3 Scaled PM2.5 concentrations during the 10-day winter sampling period

Location no.	Measuring sites	24h-1	24h-2	24h-3	24h-4	24h-5	24h-6	24h-7	24h-8	24h-9	24h-10
1.	VM	15,06	8,38	22,25	27,63	26,05	26,62	24,82	28,05	38,72	42,65
2.	SP	65,03	68,42	53,92	28,88	38,6	42,02	42,16	45,68	31,7	13,86
3.	JV	48,61	47,77	34,57	21,81	29	37,38	33,76	35,58	26,48	17,96
4.	HV 4	32,19	35,15	36,55	26,37	16,79	14,31	10,9	10,94	13,45	34,42
5.	HV 11	22,85	22,11	27,62	21,85	33,86	31,05	23,55	29,24	36,3	23,18
6.	BPP	34,97	39,96	48,96	32,53	21,14	17,04	13,71	13,38	13,99	
7.	BK	25,82	23,67	24,2	20,93	16,95	26,05	31,73	44,52	31,97	19,33

According to the conducted basic statistical analysis, expressed through *AVG*, *SD*, *MED*, minimum (min) and maximum (max) values, shown in Tab. 4, the ranges of scaled 24 hour data values during the winter season, varied significantly depending on the measurement location, ranging from 8,38 - 68,42 $\mu g/m^3$. Minimum and maximum concentrations among all seven locations ranged from 8,38 - 42,65 $\mu g/m^3$ (on VM), 13,86 - 68,42 $\mu g/m^3$ (SP), 17,96 - 48,61 $\mu g/m^3$ (JV), 10,9 - 36,55 $\mu g/m^3$ (HV 4), 21,85 - 36,3 $\mu g/m^3$ (HV 11), 13,38 - 48,96 $\mu g/m^3$ (BPP) and from 16,95 - 44,52 $\mu g/m^3$ (BK). *AVG* $PM_{2.5}$ values on these locations were 26,02 $\mu g/m^3$ (VM), 43,03 $\mu g/m^3$ (SP), 33,29 $\mu g/m^3$ (JV), 23,11 $\mu g/m^3$ (HV 4), 27,16 $\mu g/m^3$ (HV 11), 26,19 $\mu g/m^3$ (BPP) and 26,52 $\mu g/m^3$ (BK). Higher *SD* values observed at SP (± 16,52 $\mu g/m^3$) indicated significant variability in $PM_{2.5}$ concentrations during the measurement period. This variability is likely a direct consequence of mixed heating practices during the winter, including wood, coal, and gas heating, prevalent in the residential DH area where SP is located. Elevated particle concentrations at SP are consistent with the area's mixed heating systems and variations in daily combustion activities. Similarly, moderate *SD* values for the BPP, HV 4, and JV suggest considerable particle variability. The BPP and HV 4 locations are positioned near the border of DH and TPP areas, which are subject to fluctuating emissions from both district heating systems and industrial activities. JV, on the other hand, experiences high traffic intensity, further contributing to the variability observed in this area. Conversely, lower *SD* values at HV 11 and BK indicate more stable $PM_{2.5}$ concentrations during the 10 day period. These locations are primarily influenced by emissions from TPP areas, where medium to low traffic intensity and consistent industrial operations are likely to result in less variability. The *MED* values highlighted some degree of skewness in the data, which could be attributed to concentration peaks during the short measurement period. Given the limited 10 day sampling duration, these results are more sensitive to episodic pollution events, such as increased heating demand on particularly cold days or spikes in traffic emissions.

Table 4 Statistical parameters for winter period

Location no.	Measuring sites	*AVG*	*SD*	*MED*	min	max
1.	VM	26,02	9,95	26,34	8,38	42,65
2.	SP	43,03	16,52	42,09	13,86	68,42
3.	JV	33,29	10,00	34,17	17,96	48,61
4.	HV 4	23,11	10,82	21,58	10,9	36,55
5.	HV 11	27,16	5,26	25,59	21,85	36,3
6.	BPP	26,19	13,24	21,14	13,38	48,96
7.	BK	26,52	7,96	25,01	16,95	44,52

During the summer season, scaled $PM_{2.5}$ concentrations exhibited less variability, which can be explained by the presence of fewer heterogenic emission sources outside the frame of the heating season. The concentration ranges for all locations were between 2,37 and 18,31 µg/m^3. Compared to the WHO recommended daily limit of 15 µg/m^3 for $PM_{2.5}$, it was observed that concentrations at the BPP location exceeded the limit on only one occasion during the 10-day sampling period. At HV 4 and JV, the concentrations remained below 15 µg/m^3 throughout the entire period, reflecting more stable and lower pollution levels. However, at the remaining locations, the WHO-recommended limit was exceeded in six to seven days, indicating localized variations in pollution sources. Summer scales $PM_{2.5}$ concentrations are presented in Tab. 5. Tab. 5 employs the same color scheme as winter measurements but reveals fundamentally different pollution patterns, with green zones at HV 4 and JV indicating consistently safe air quality levels (< 15 µg/m^3). The recurring orange markers at HV 11 (peaking at 18,31 µg/m^3) and SP clearly identify summer-specific pollution hotspots driven by traffic emissions and construction activity. Most significantly, the complete absence of red - which dominated winter readings provides immediate visual confirmation of the seasonal transition from heating-related to mobile-source pollution. Beyond simple classification, these color patterns serve as a spatial decision-support tool: the persistent orange zones around major intersections like HV 11 represent high-priority targets for warm-season traffic interventions, while the stable green areas validate the effectiveness of existing pollution controls in certain neighborhoods.

Table 5 Scaled PM2.5 concentrations during 10-day summer sampling period

Location no.	Measuring sites	24h-1	24h-2	24h-3	24h-4	24h-5	24h-6	24h-7	24h-8	24h-9	24h-10
1.	VM	9,01	13,6	17,4	17,35	18,52	21,18	20,98	18,54	9,19	12,13
2.	SP	17,16	16,14	19,46	11,4	15,76	23,15	22,59	16,84	15,78	11,68
3.	JV	10,99	11,79	8,7	13,05	12,41	12,06	7,51	7,58	11,9	14,57
4.	HV 4	9,49	14,25	14,18	11,8	7,57	10,49	13,83	14,42	13,51	7,13
5.	HV 11	10,97	12,68	17,19	19,57	21,01	23,35	24,38	19,42	9,33	12,81
6.	BPP	9,73	14,27	13,69	11,32	7,21	10,32	13,46	15,64	14,21	6,83
7.	BK	16,86	19,8	16,97	11,95	11,05	14,89	18,35	20,65	16,67	8,24

The minimum and maximum values of $PM_{2.5}$ concentrations for each measuring site highlight notable differences between locations. For instance, at VM, the range was from 4,52 to 17,38 µg/m^3, while SP showed values between 3,92 and 17,00 µg/m^3.

Table 6 Statistical parameters for summer period

Location no.	Measuring sites	*AVG*	*SD*	*MED*	min	max
1.	VM	15,79	4,52	17,38	4,52	17,38
2.	SP	17,00	3,92	16,49	3,92	17,00
3.	JV	11,06	2,37	11,85	2,37	14,57
4.	HV 4	11,67	2,83	12,66	2,83	12,66
5.	HV 11	17,07	5,32	18,31	5,32	18,31
6.	BPP	11,67	3,08	12,39	3,08	12,39
7.	BK	15,54	4,00	16,77	4,00	16,77

Similarly, JV, HV 4, HV 11, BPP, and BK exhibited ranges of 2,37 - 14,57 µg/m^3, 2,83 - 12,66 µg/m^3, 5,32 - 18,31 µg/m^3, 3,08 - 12,39 µg/m^3, and 4,00 - 16,77 µg/m^3, respectively. The highest measured concentrations were recorded at HV 11 (18,31 µg/m^3) and VM (17,38 µg/m^3) situated near the major intersections, as well as at SP (17,00 µg/m^3). Since the SP site is in a resident area with very low resident traffic, these higher concentrations could be attributed to construction activities and the use of active machinery during ongoing building projects.

The *SD* values during the summer period revealed a degree of variability in the data, particularly at SP and HV 11, while the *MED* values indicated an obvious impact of higher values within a relatively small set of data since *MED* values were crossing *AVG* values. The study highlights significant seasonal differences in $PM_{2.5}$ concentrations in Novi Sad, with higher levels observed during winter, influenced by mixed heating systems and local traffic, particularly at SP and HV 4. These findings align with those in [18], which emphasized the impact of solid fuel heating, and in [19], which identified traffic and industrial emissions as critical contributors to seasonal variability. In contrast, lower and more stable $PM_{2.5}$ levels were recorded during summer, consistent with [19] findings on the reduced impact of heating. Notably, at SP, construction activities emerged as a key source of summer pollution, highlighting the influence of localized factors. These results underscore the need for tailored mitigation strategies addressing specific seasonal and site-specific emission sources to improve urban air quality.

Pronounced spatial $PM_{2.5}$ concentration variations in winter compared to the summer season trends, besides evident heterogeneity and higher intensity of emission sources in the heating season, were in a certain extent the result of low-cost sensor sensitivity on increased humidity in winter (60 - 80%). This claim was also confirmed by [20], whose author reported low-cost sensor sensitivity and decline with RF devices when humidity in ambient air is above 75%. Therefore, frequent evaluation processes of low-cost devices, using techniques of collocating low-cost devices with reference stations and calibrating them, are necessary to ensure the reliability and efficiency of air quality measurements with these devices.

3.3 Health Risk Assessment

The particle measurement periods within this study do not align with usual time frame of at least 365 days of exposure required for determining chronic health risk, as specified by the [17]. However, the health risk assessment was approached as the preliminary evaluation of chronic risk for pedestrians living in the urban area of the Novi Sad City, based on exposures to seasonal $PM_{2.5}$ variations. A similar approach to preliminary health risk determination was conducted by [16], who utilized shorter-term measurements due to the absence of long-term data. Likewise, [15] assessed health risks, including the Lifetime Average Daily Dose (*LADD*) and risk quotients, based on four months of measurements for pedestrians and cyclists. Furthermore, findings from studies like [21], indicate that short-term exposure assessments can provide critical insights into acute health risks associated with $PM_{2.5}$ exposure; specifically, it was demonstrated that every 10 $\mu g/m^3$ increase in $PM_{2.5}$ exposure correlates with a 2.8% rise in PM-related mortality (95% *CI* = 2,0 - 3,5), thereby reinforcing the relevance of our approach in evaluating potential chronic health impacts even with limited measurement durations.

The consistent seasonal particle emission patterns observed during winter in Serbia, including Novi Sad, provide a valid foundation for estimating preliminary chronic risks. Assessing chronic risks from $PM_{2.5}$ using short-term measurements is especially relevant for the seven monitored locations, as there are no nearby regular monitoring stations, and these parts of the city are densely populated. The characteristics of these sites such as urban configurations, emission sources, and varying traffic intensities represent many areas across the city. The calculated preliminary chronic risks (PrChR) were evaluated from two perspectives: first, the seasonal health risks affecting the defined population, and second, the spatial distribution of risks, observed through hazard quotients (*HQ*s) between the monitored locations.

3.3.1 Seasonal Health Risk Assessment

Across both seasons, analysis of average hazard quotients (*HQ*s) from seven locations indicated that males generally faced greater preliminary chronic risks (PrChRs) from air pollution than females. During winter, average *HQ* values for males across the age groups 3 - 9, 10 - 17, 18 - 29, 30 - 59, and > 60 years were 3,76; 3,35; 3,71; 3,79; and 3,76, respectively, as presented in Fig. 5. For females, the corresponding *HQ* values were 2,10; 3,05; 3,46; 3,60; and 3,60. The analysis revealed that males are at a higher risk than females. This aligns with studies such as [22, 23], which suggest that males are more vulnerable to ambient $PM_{2.5}$ exposure than females, especially in colder seasons. In addition, variations in hormonal influences on immune response and oxidative stress might contribute to gender specific vulnerabilities [24]. Further, among age groups, the 30 - 59 years demographic exhibited the highest risk, followed by the 3 - 9 years and > 60 years groups. A relatively lower risk, with *HQ* values near 2, was observed only among females aged 3 - 9 years, while *HQ*s for other groups consistently exceeded 3. The overall average *HQ* values across all age groups were above 1, underscoring the potential chronic health risks associated with prolonged exposure to winter pollution over the years. Based on the WHO report from 2019, in Serbia's urban areas, the total of 221626 years of life for adults aged ≥ 30 years, were lost over a 10- year period due to $PM_{2.5}$ air pollution. Men lost 112076 years, while women lost 108986 years of life over a 10 year period. This high number reflects the serious impact of air pollution on health in Serbia's urban cities [25].

Regarding the summer season, the *AVG HQ* values dropped significantly compared to the winter period, indicating a reduced overall health risk from air pollution. The stark contrast between health risks in winter and summer underscores the influence of seasonal variations in pollutant concentrations and exposure patterns. Winter is associated with higher levels of $PM_{2.5}$ due to increased emissions from heating systems and stagnant atmospheric conditions, which limit pollutant dispersion. Factors such as increased ventilation, higher atmospheric mixing, and lower emissions from heating systems contribute to this seasonal disparity. The average *HQ*s during summer for males in the age groups 3 - 9, 10 - 17, 18 - 29, 30 - 59, and > 60 years were 1,12; 1,64; 1,83; 1,87 and 1,86 respectively, as shown in Fig. 6. For females, the respective *HQ* values were 1,02; 1,48; 1,67; 1,74 and 1,70. None of the *HQ* values during the summer exceeded 2 for either gender or any age group, reflecting a notably lower health risk compared to winter. This reduction is likely to be attributable to lower pollutant concentrations resulting from factors such as reduced heating demands and altered atmospheric conditions. The highest *HQ* values during summer were recorded in the 30 - 59 and > 60 years age groups for both genders, with males showing values of 1,87 and 1,86, and females exhibiting 1,74 and 1,70.

Males consistently exhibited higher *HQ* values across all age groups, though the gender disparity was less pronounced in summer compared to the winter season. These gender disparities in *HQ* values may be due to differences in exposure patterns and activities. Comparison of gendered-based activities across different communities can provide valuable exposure measurement data [24]. For example, males may engage in more outdoor activities or have occupations that involve higher exposure to ambient air pollution during winter, contributing to elevated *HQ* values. Conversely, in summer, reduced indoor heating emissions and generally better air quality create more uniform exposure patterns, leading to smaller gender-based differences [23]. Observing statistical data from the Eurostat database and the period of 2008 - 2015, in Serbia, women are more involved in household and family care activities compared to men, with 98% for females and 77% for males [26]. From an age-based perspective, the highest *HQ* values were observed in the 30 - 59 and > 60 age groups for both genders during winter. This is consistent with studies highlighting the increased vulnerability of middle-aged and elderly populations to particulate pollution due to higher baseline incidences of cardiovascular and respiratory conditions [22]. The greater risk in these age groups may also be attributed to cumulative lifetime exposure and physiological factors such as reduced pulmonary function and weakened immune systems. Interestingly, the 3 - 9 years age group exhibited lower *HQ* values in comparison but still faced notable health risks (*HQ* > 2 in winter). Young children's vulnerability arises from their developing respiratory systems and higher breathing rates relative to body size. However, the lower *HQ* values compared to adults may be partially attributed to differences in activity patterns, such as spending less time outdoors in polluted environments [27]. Several factors could also explain these gender differences. One critical aspect is the physiological differences between males and females, including higher inhalation rates and body mass in males, which can result in increased pollutant uptake during daily activities [23]. Notably, the 3 - 9 years age group, in particular, displayed a minimal difference in *HQ* between males and females during summer, contrasting with the more substantial disparities observed in winter. This suggests that environmental conditions in summer may lead to more uniform exposure between young males and females, possibly due to reduced activity-related differences in pollutant uptake or variations in environmental exposure factors [28]. Although some studies report females as being more susceptible to air pollution due to their higher prevalence of preexisting conditions like COPD and asthma and greater exposure to indoor air pollutants [29], others, including [16, 30-32], support the findings here that males show higher susceptibility. In the case of [31] greater association was found between long-term exposure to $PM_{2.5}$ pollution in the air and increased mortality risk for men due to cardio-cerebrovascular and cancer diseases. Similarly, [30] approved a higher cause-and-effect relationship between $PM_{2.5}$ and lung cancer mortality in the case of males. According to a meta-analysis that examined relationships between exposure to $PM_{2.5}$ and lung cancer and mortality for both genders, the meta-estimate for lung cancer mortality and meta-estimate for lung cancer incidence associated with $PM_{2.5}$ was greater for males than females [32]. This discrepancy may stem from regional differences in pollutant composition, as the chemical makeup of $PM_{2.5}$ varies significantly depending on local emission sources and meteorological conditions [28]. For example, the higher proportion of combustion-related pollutants during winter in Serbia, including soot and polycyclic aromatic hydrocarbons, may disproportionately impact male physiology, leading to elevated *HQ* values [25, 33].

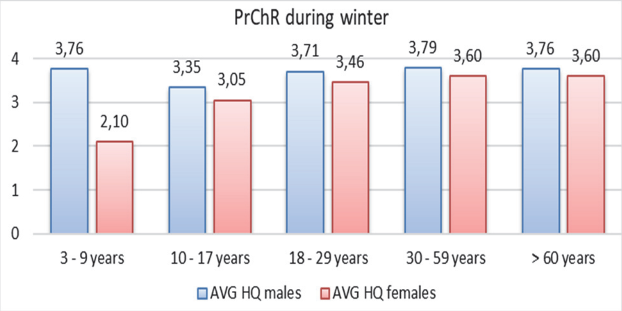


Figure 5 *AVG HQ*s for males and females during winter season

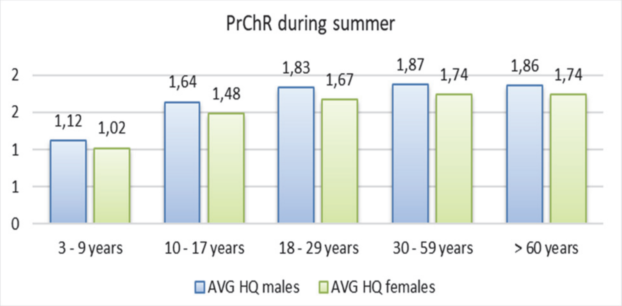


Figure 6 *AVG HQ*s for males and females during summer season

3.3.2 Spatial Variations of *HQ* Values for PrChRs During Winter and Summer

Preliminary ChRs during the winter season were analysed to identify the highest chronic risks among measured sites, genders, and age groups (Fig. 7). Based on the analysis of *HQ* values, SP emerged as the most hazardous location for all age groups, with the highest risk values observed in the 30 - 59 age group (5,57 for men, 5,26 for women), followed by the 18 - 29 age group (5.46 for men, 5,05 for women) and > 60 age group (5,51 for men, 5,26 for women). The risks were particularly pronounced among men but were also notably high for women in these groups. JV also exhibited elevated risks, especially for the 30 - 59 age groups (4,23 for men, 4,07 for women) and 18 - 29 age groups (4,15 for men, 3,90 for women). At the BK site, the risks were more prominent among women, particularly in the 30 - 59 and > 60 age groups (3,67 for women in both categories), where women experienced higher risk values than men. In addition to the mentioned places, HV 11 and HV 4 also demonstrated elevated risk values, although they were slightly lower compared to SP and JV. At HV 11, the risks were notable in the 30 - 59 age group, with values for men (3,55) exceeding those for women (3,32). The risks for women were lower than at the SP site, but still significant. Similarly, the HV 4 site presented moderate risk values ranging from 2,75 to 3,10, although these were generally lower than those recorded at SP and JV. These locations are categorized as moderate-risk sites and warrant continuous monitoring, as they still pose significant risks for certain age groups. The VM and BPP sites displayed lower risks compared to the aforementioned locations. *HQ* values at VM ranged from 1,99 to 3,39 for men and from 1,85 to 3,18 for women, while at BPP, values ranged from 2.01 to 3,29 for men and from 1,68 to 2,88 for women. Despite lower risk levels, age groups 18 - 29, 30 - 59, and > 60 years still exhibited some degree of vulnerability, underscoring the importance of including these sites in risk assessments.

In general, the risks were higher for men across most locations, with considerable variation. However, in the 30 - 59 and > 60 age group, the risk was significant for both genders. Special attention should be given to the women in the older age groups (30 - 59 and > 60 years), especially at the BK site, where they exhibited particularly high risks, which is in agreement with the findings of the study by [34].

During the summer season, the highest preliminary chronic risks due to inhalation of ambient air polluted with $PM_{2.5}$ particles were observed at HV 11 and SP (Fig. 8). HV 11 recorded the highest *HQ* values across all age groups, with particularly elevated risks for men in the 30 - 59 (2,25), 18 - 29 (2,20), and > 60 (2,24) age groups, while women displayed slightly lower, but still significant values (2,09 for 30 - 59 and > 60 age groups). SP exhibited high risk in all age groups, though slightly lower than HV 11, with *HQ* values for men in the age groups 30 - 59 (2,23) and > 60 (2,21), but also for women in the age groups 30 - 59 (2,08) and > 60 (2,08). Moderate risks were observed at VM and BK, with men in older age groups showing elevated risk values up to 2,11 for VM (30 - 59 years) and 2,02 for BK (30 - 59 years). Sites BPP, HV 4, and JV exhibited lower risk levels, with *HQ* values up to 1,55 for BPP and HV 4 (30 - 59 years) and 1,40 for JV (30 - 59 years). Despite these lower values, older individuals remained significantly exposed, emphasizing the need for continued surveillance at these locations.

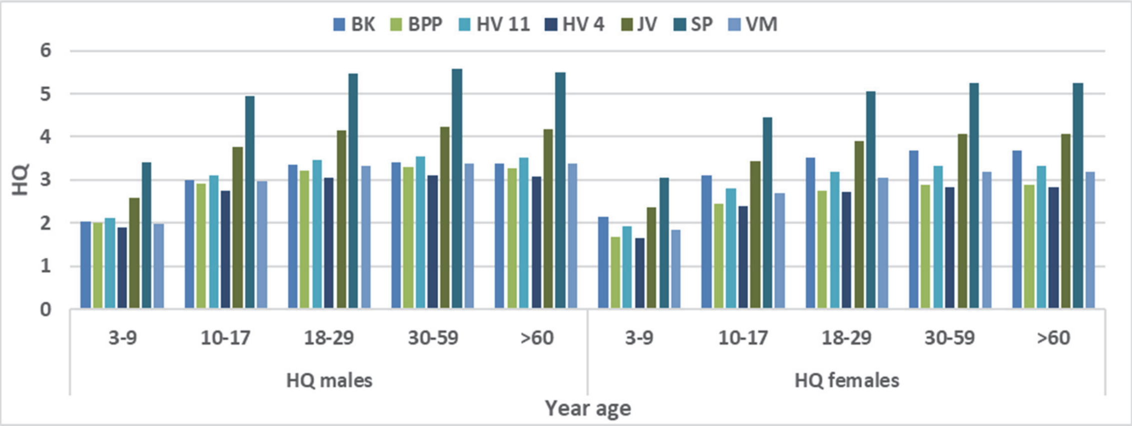


Figure 7 Average daily *HQ* for winter

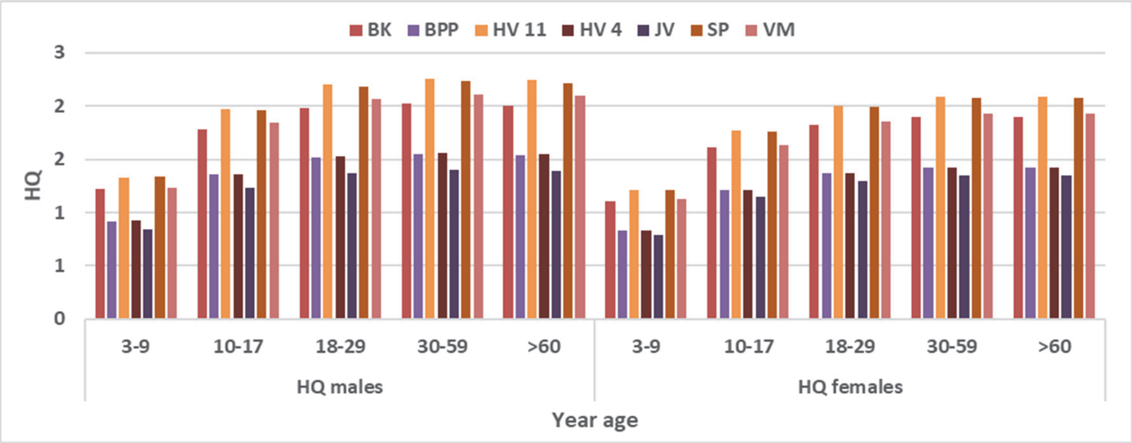


Figure 8 Average daily *HQ* for summer

The observed variations in *HQ* values across different locations and seasons can be attributed to several key factors. During the winter season, elevated *HQ* values at SP and JV are likely associated with increased emissions from residential heating, atmospheric transport of industrial activities, and reduced atmospheric dispersion due to lower temperatures and frequent temperature inversions. These conditions exacerbate the accumulation of fine particulate matter ($PM_{2.5}$) and associated pollutants, contributing to heightened health risks, particularly for sensitive age groups [15]. The pronounced risks at SP for both genders, and especially among men, may reflect the site's proximity to major emission sources such as traffic-dense areas, garages of city transport vehicles, or inadequate urban planning that limits pollutant dispersal [35]. Similarly, the elevated risks at JV suggest localized contributions from transportation-related emissions, or atmospheric transport of industrial activities, further compounded by meteorological factors during the winter. In contrast, HV 11 and HV 4, although showing significant risks, exhibit slightly lower *HQ* values due to factors such as lesser traffic intensities, greater distance from major pollution sources like residential areas, or the absence of vertical physical barriers that contribute to pollution accumulation.

During the summer, the highest risks at HV 11 and SP, can be related to the vicinity of big intersection and parking lots at HV 11, while at SP during summer, great particle emissions are possible due to the presence of machinery at active construction sites in the immediate vicinity. Besides these actual emission sources, these health risks can also be attributed to enhanced photochemical reactions that produce secondary pollutants, including $PM_{2.5}$, under higher temperatures and solar radiation. This seasonal effect, combined with continuous anthropogenic emissions, explains the persistent health risks during this period. The lower risks observed at VM and BPP suggest reduced exposure levels, potentially due to fewer nearby emission sources or more favorable dispersion conditions in these areas due to a lighter urban environment where better circulation of air masses is enabled. However, the moderate risks identified at these sites indicate that localized sources still contribute to $PM_{2.5}$ concentrations, warranting continued monitoring. Additionally, the higher risks for women in certain age groups at specific sites (e.g., BK) suggest potential differences in exposure patterns or health vulnerabilities, underscoring the importance of targeted risk mitigation strategies.

4 CONCLUSION

This study highlights the significant impact of seasonal and spatial variations in $PM_{2.5}$ pollution on public health in Novi Sad. It emphasizes the urgent need for localized health risk assessments, particularly in areas without regular air quality monitoring. The findings reveal that winter poses the highest health risks, with $PM_{2.5}$ levels significantly exceeding recommended thresholds due to residential heating and traffic emissions. The most vulnerable groups, particularly middle-aged and elderly males, face an elevated risk of chronic exposure, emphasizing the need for season-specific mitigation measures.

Seasonal trends indicate that winter pollution is driven by intensified heating emissions and reduced atmospheric dispersion, necessitating urgent policy action to promote cleaner heating technologies and stricter emission controls. In contrast, summer air quality was generally better; however, localized pollution hotspots persisted, particularly in areas affected by traffic congestion and construction activities, indicating that year-round pollution management strategies are essential.

Beyond seasonal variations, spatial analysis revealed significant disparities among the seven monitored locations. The highest risks were observed at SP and HV 11, where $PM_{2.5}$ concentrations consistently exceeded WHO guidelines due to mixed heating systems and heavy traffic. In contrast, HV 4 and BPP exhibited lower pollution levels, though still influenced by seasonal fluctuations. These findings highlight the role of urban morphology, emission sources, and land use patterns in shaping pollution exposure, reinforcing the need for site-specific mitigation strategies.

Effectively addressing chronic health risks associated with $PM_{2.5}$ exposure requires an integrated, multi-faceted approach. This includes continuous air quality monitoring, stricter environmental regulations, and long-term epidemiological studies to refine risk assessments. Understanding both when and where pollution poses the greatest health risks enables the implementation of evidence-based interventions that enhance urban air quality and safeguard public health. The insights from this study provide a foundation for future research and policy development, emphasizing the necessity of proactive, year-round air pollution management to mitigate adverse health impacts in urban environments.

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