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DEFINING THE PATTERNS OF CHANGE IN PM2.5 CONCENTRATIONS IN KYIV UNDER MILITARY LOAD BASED ON SCENARIO ANALYSIS

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This study examines the process of formation and change of the atmospheric air state over an urbanized territory under conditions of military-technogenic load. The task addressed is to define features in the spatial-temporal dynamics of PM2.5 concentrations under the influence of military load on urbanized territories.

The work has assessed the impact of massive air attacks on the state of the atmospheric air in the city of Kyiv in 2025 based on the fine PM2.5 particles concentrations. The study used data from air quality monitoring networks aggregated at the SaveEcoBot platform (Ukraine), as well as information on the nature, intensity, and consequences of military events in the capital's districts.

An integrated scenario approach to assessing the relationship between shelling and changes in PM2.5 concentrations has been proposed, based on a combination of spatial, temporal, and event characteristics. The methodology takes into account the background values of PM2.5 concentrations for each district, as well as the type of local impact of military events. Within the model, scenarios of direct and indirect impact, deterioration of air quality without shelling, situations without a significant increase in PM2.5 and control cases were distinguished.

It was established that the largest share of observations (80.2%) is made up of cases of possible indirect impact – 340 episodes associated with the transfer of combustion products from the fire site and secondary aerosol pollution. For the category of direct possible impact, 28 cases (6.6%) were recorded at the highest average value of the integrated index of 0.79, which corresponds to a high level of connection between military events and deterioration of air quality. It has been shown that military events form short-term periods of extreme atmospheric air pollution.

The results of the study lay the groundwork for further integrated assessment of the combined impact of atmospheric, technogenic, and military factors on urbanized areas

Keywords: PM2.5, fine aerosols, environmental safety, monitoring, scenario analysis, military impact

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1. Introduction

The issue of natural and technological safety of the regions in Ukraine has acquired in 2022–2026 a new meaning because of the imposition of military impacts on "classical" technological risks (industrial accidents, fires, emissions, infrastructure degradation). The war in Ukraine is considered in the international literature not only as a humanitarian crisis but also as a factor of systemic environmental damage – from the degradation of soils and water ecosystems to the disruption of climate characteristics due to unaccounted emissions [1].

For Ukrainian circumstances, the integration of three levels of analysis is key:

– identification of threat sources (high-risk objects, critical infrastructure, combat zones);

– assessment of environmental damage (atmosphere, soil, surface and groundwater, biota);

– assessment of vulnerability and ability to restore regional socio-ecological and technical systems.

Such approaches are based on the vulnerability of critical infrastructure interdependencies, which is especially relevant in the context of attacks on energy, water supply, transport hubs, and industrial sites [2].

Current risk assessments in natural-technological safety increasingly describe the object of study as an interconnected "human-environment" system in which risk is determined not only by exposure to hazards but also by the sensitivity and resilience of the system [3]. In the classical sense, it is necessary to simultaneously take into account the external impact, the internal characteristics of the system, and the system's response to this impact. Under war conditions, these components change faster: the frequency of "extreme" impacts (explosions, fires, etc.) increases, and the ability to respond to events decreases due to access restrictions, resource shortages, and population displacement [4].

In international practice, technogenic accidents caused by external extreme impacts are described as Natech (natural-hazard triggered technological accidents) [5]. For Ukraine, the concept of Natech is important in two aspects [6]. First, even "peaceful" natural events (floods, heat, fire hazard) can exacerbate the consequences of infrastructure degradation during war. Secondly, military influence often acts as a trigger similar to a natural extreme: a strike on an industrial site, fuel and lubricant tanks, chemical reagent warehouses, or treatment facilities can trigger an accident with subsequent escalation.

Therefore, it is a relevant task to assess natural and man-made safety in Ukraine, necessary for understanding the interaction among natural, man-made, and military factors, their combined impact on the environment. Such studies will contribute to devising effective approaches to risk management, increasing the resilience of infrastructure, and ensuring environmental security under conditions of prolonged instability.

2. Literature review and problem statement

Analytical studies on the war in Ukraine state that environmental damage is formed in several directions. Among key drivers are destruction of industrial infrastructure and warehouses of hazardous substances, explosions and fires, damage to water and energy networks, etc., secondary effects due to disruption of monitoring and control systems.

There is evidence of severe air pollution and greenhouse gas emissions as a result of intense fighting. Biodiversity has been severely affected by intensive deforestation and burning of forests with potential consequences for wildlife. Bombing, excavation of trenches and tunnels negatively affect soil degradation and landscape morphology. Water availability and quality suffer because of destruction of infrastructure and transfer of pollutants to water bodies [2].

Additionally, volley emissions and discharges caused by military operations can be associated with risks to public health. In particular, work [7] reports an analysis of the threats of chemical contamination of territories from long-range weapons used by the Russian Federation against Ukraine. The authors assessed various types of ballistic and cruise missiles that attacked regions of Ukraine in terms of their danger of chemical contamination of the environment due to fuel leakage after the fall. It was shown that the most chemically dangerous are the Soviet cruise missile Kh-22 and its modernized version Kh-32, which use a two-component composition as fuel: fuel – TG-02 (samin), oxidizer – AK-27I (mélange). The use of these components is prohibited by international conventions [8] and state regulations [9, 10]. In particular, document [8] describes the humanitarian and environmental risks arising from mélange and samin, indicates the relevant aspects of storage and processing, as well as highlights various methods of elimination. The cited review brings together best practices for liquid rocket fuel disposal over the past 50 years to provide OSCE participating states with information and analysis for devising policies, general recommendations, and procedures for the disposal of their unusable or surplus liquid rocket fuel components, mainly mélange and samin. The Cabinet of Ministers of Ukraine's orders "On the approval of the list of liquid rocket fuel components subject to disposal" in 2013–2014 [9] and 2015–2016 [10] specifically address the destruction of these two rocket fuel components – mélange and samin. Although less aggressive fuels are used in unmanned aerial vehicles (UAVs), their use in attacks increases the level of environmental hazards.

Military operations create atmospheric risks through fires at infrastructure facilities, detonation of ammunition, destruction of building materials, and secondary dust from contaminated soils. In [11], a technique of remotely sensed air quality using the aerosol optical depth (AOD) as a remote indicator of air quality was used to analyze the air quality in Ukraine before and during the war. The study analyzed AOD products obtained using MODIS Multi-Angle Implementation of Atmospheric Correction (MAIAC) satellite analysis. By studying the spatiotemporal distribution of AOD in 2022 and comparing it with the base period from 2012 to 2021, the authors assessed the impact of the military conflict on the state of atmospheric air. In order to determine the change in the physical and optical properties of aerosols over Ukraine during the war, the work analyzed four parameters from the Aerosol Robotic Network (AERONET) measurements in the Kyiv area. The following parameters were recorded during the research: single scattering albedo (SSA), refractive index (RI), and fine mode fraction (FMF). The overall result of the study indicates a national-"contradictory" effect, namely, the air quality in Ukraine has been subject to a contradictory impact of the war at different levels. At the national level, atmospheric pollution throughout Ukraine has decreased due to a decrease in pollutant emission sources as a result of the decline in economic and agricultural activity. At the same time, atmospheric air quality has deteriorated at the local level, where the war is intense, due to a large number of pollutants released into the air as a result of explosions. After the start of the full-scale war on February 24, a significant increase in AOD was observed in March compared to the baseline period. In eastern Ukraine, a significant increase in AOD by 40.14% was recorded, while in the north and central part of Ukraine an increase of this indicator by 34.15% and 45.78% was observed, respectively. In April of the same year, compared to March, areas with significantly higher AOD values were observed to spread across Ukraine. In July, large areas with anomalously low AOD appeared in northern and western Ukraine. In August, areas with anomalously high AOD were observed in central Ukraine, possibly related to continued Russian long-range strikes and a new cycle of bombing.

The problems of the national-"contradictory" effect in assessing environmental risks by regions of the country under conditions of military conflict were also discussed in paper [12]. The authors prove that under crisis conditions the semantics of key indicators undergo qualitative changes, as a result of which traditional interpretations of their dynamics become incorrect. The algorithm for calculating the integrated index of environmental security proposed by the researchers involves checking the stability of regional indicators in terms of completeness and reliability of statistical data, increases the adequacy of assessing environmental risks during the conflict. This, in turn, increases the readiness of the environmental monitoring system for emergencies and contributes to the formation of a stable methodological base for assessing environmental risks.

For the urban environment, short-term peaks in PM2.5/PM10, which coincide with attacks and fires, are critical. The authors of the study in Urban Science [13], using a network of low-cost sensors, demonstrate PM2.5 spikes in Kyiv during combined missile and drone strikes and emphasize the importance of public monitoring as a source of evidence. In work [14], a clear example of a point source of anthropogenic pollution of military origin is given for the fire at the Kalynivka oil depot as a result of a missile strike in March 2022, estimating the emissions of CO_2, NO_x, SO_2, soot, and PM2.5/PM10 fractions.

Our review of the literature [11, 15–18] allows us to identify several system gaps that are of critical importance for devising a methodology for assessing man-made and military threats. First, many papers record consequences at the level of individual components of the environment (water, air, soils), but much less often offer integrated models of cascading effects between components and infrastructures [15]. Secondly, existing pollution indices often do not take into account the "dual" nature of the impacts – the pre-war man-made background plus the war trigger – which can change the interpretation of excesses and risk indices [16, 17]. Third, remote sensing approaches are sometimes highly sensitive to meteorological conditions (for example, for AOD [11]) and need to be combined with ground measurements and scenario analysis [11, 18].

Studies on the war and natural and man-made risks show that a country in a state of military conflict requires an extraordinary methodology of risk assessment. The main requirements for such non-traditional methods are the simultaneous consideration of man-made and military impacts, recording of cascading infrastructure failures, the establishment of relationships between environments and the determination of long-term consequences of pollution. Thus, further research should move towards an integrated assessment based on formalized scenarios and quantitative uncertainty considerations. A mandatory and primary attribute of all studies should be representative sets of updated spatial indicators (remote sensing, official monitoring posts) [13, 19, 20].

All this allows us to state that it is appropriate to conduct a study aimed at devising approaches to the integrated assessment of the combined impact of various factors (atmospheric, man-made, military) at the regional level.

3. The aim and objectives of the study

The aim of our study is to define patterns of changes in the PM2.5 concentrations in Kyiv under the influence of military load, by means of statistical analysis of spatial-temporal data from monitoring the city's atmospheric air. This will make it possible to improve approaches for the integrated assessment of the combined effects of atmospheric, technogenic, and military factors on urbanized areas.

To achieve the goal, the following tasks were set:

– to conduct an analysis of spatial-temporal changes in PM2.5 concentrations in 10 districts of Kyiv during 2025;

– to assess the role of massive air attacks for inducing local and regional changes in air quality;

– to perform a statistical assessment of scenarios of the relationship between military events and changes in PM2.5 concentrations.

4. The study materials and methods

4. 1. The object and hypothesis of the study

The object of our study is the process of formation and change of the state of atmospheric air over urbanized territories under conditions of military-technogenic load.

The principal hypothesis assumes that massive air attacks and the associated fires and destruction of infrastructure lead to a significant short-term increase in PM2.5 concentrations in the air of the city.

Assumptions adopted: the use of average background values of PM2.5 for individual districts makes it possible to correctly assess relative changes in the quality of atmospheric air under conditions of aerosol pollution of various origins.

Simplifications accepted: data from monitoring points on PM2.5 concentration are representative for assessing the state of atmospheric air in districts of Kyiv, despite differences in types of equipment and density of spatial coverage; complex atmospheric processes of aerosol transport were not taken into account.

4. 2. General characteristics of the study area and the current state of atmospheric air in the city of Kyiv

In this work, the research was conducted on the territory of the city of Kyiv (Fig. 1), characterized by significant anthropogenic and military loads. According to [21], in 2024, the total population in the city was 2952,301 thousand people living on 835.6 km^2.

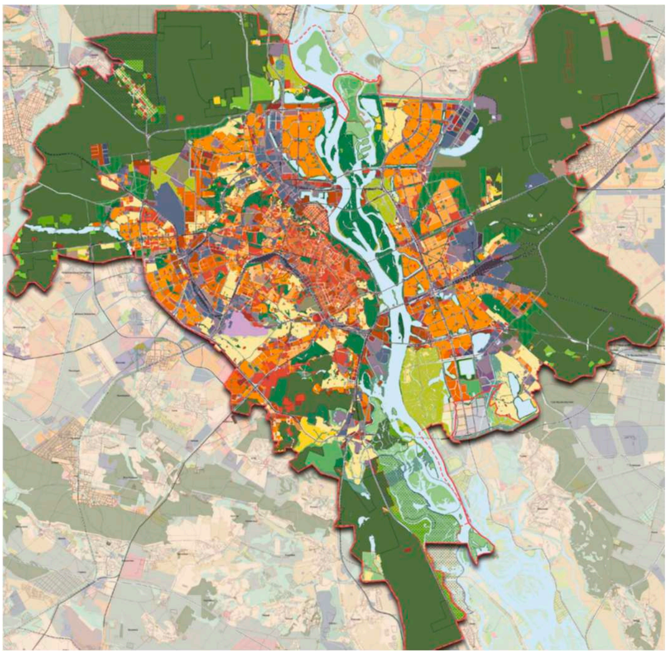


Fig. 1. Map of the city of Kyiv [21]

An analysis of the city's air quality was conducted for 2025, which was marked by a significant increase in the number of combined drone and missile attacks targeting Kyiv's energy system. The World Bank [22] and the United Nations [23] in their reports noted the enormous damage to the city's energy infrastructure caused during 2025.

The total anthropogenic impact on the city's air remained quite significant [24] (Fig. 2).

Thus, according to the Air quality and pollution city ranking [24], with the beginning of the full-scale war, the average annual concentration of PM2.5 decreased from 18.8–19.2 points to 8.9–9.5 points due to the decline in production in the city and the decrease in the population. Starting from 2024, this indicator gradually increased to 9.4 points and 10.0 points, which was the total result of the activities of enterprises, motor vehicles, and destructive shelling.

PM2.5 legend

0-5	5.1-10	10.1-15	15.1-25	25.1-35	35.1-50	>50.1
Meets WHO guideline	Exceeds by 1 to 2 times	Exceeds by 2 to 3 times	Exceeds by 3 to 5 times	Exceeds by 5 to 7 times	Exceeds by 7 to 10 times	Exceeds by over 10 times

Rank	City	2025	2024	2023	2022	2021	2020	2019	2018	2017
3053	Kyiv, Ukraine	10	9.4	8.9	9.5	18.8	19.2	16.6	13.8	9.8
7962	Stockholm, Sweden	5.2	5.3	5.4	6.8	6	5.1	6.1	6.6	4.4

Fig. 2. Dynamics in the average annual concentration of PM2.5 aerosols in the air of Kyiv (2017–2025); the city of Stockholm, the capital of Sweden, was chosen for comparison

The analysis of the city's atmospheric air was assessed on the basis of annual monitoring data on the concentration of fine particles PM2.5 in the air. First, this indicator, namely PM2.5, is constantly determined in real time by the international company IQAir [24], which specializes in protection against air pollutants and works in partnership with the United Nations Environment Program (UNEP) and Greenpeace. It is IQAir data that Ukrainian and international media most often refer to when reporting that Kyiv, other cities in Ukraine or in the world, are at the top of the air pollution rating. Secondly, all city air quality monitoring platforms record PM2.5 values online [20, 25]. Thirdly, fine particles in the air (PM2.5) increase the level of potential danger to public health [26, 27]. Such aerosols are not retained by the nasopharynx, enter the lungs, and then are carried throughout the human body by the blood, causing respiratory, cardiovascular, and oncological diseases. It is fine dust in the air that is considered the scourge of megacities.

4. 3. Spatial distribution, typology, and technical features of atmospheric air monitoring points in Kyiv

We have used results of monitoring observations obtained using the integrated platform SaveEcoBot (Ukraine) [20], which is an aggregator of environmental monitoring that combines data from various state, municipal, commercial, and public networks in a single cartographic system. This platform is the most complete air quality monitoring system in Kyiv and Ukraine, which makes it possible to fully assess urban, anthropogenic, and military impacts on atmospheric air.

The aggregation of monitoring observation data from different networks has a number of advantages. These include the possibility of conducting scientific research due to the comprehensive coverage of the city both by territory and by the number of data from observation points with subsequent comparison of the values obtained. According to the SaveEcoBot platform, 398 stations have been set up in Kyiv, of which 54 are active, transmitting data in real time (Table 1, Fig. 3).

Table 1 and Fig. 3 show that the capital has an uneven distribution of monitoring points, with the maximum number of them in the Darnytskyi and Dniprovskyi districts, which are densely populated and traffic-loaded. Solomyanskyi, Obolonskyi, and Pecherskyi districts are characterized by moderate coverage. The remaining districts in the capital have a small number of points for recording atmospheric air indicators, which is explained by the peripheral location of the districts and the presence of large areas of green zones (Fig. 1).

As noted above, SaveEcoBot aggregates data from different networks, so the type of equipment depends on the specific source. In most cases, optical laser light scattering sensors are used, and reference or semi-reference analyzers are used for official stations (Tables 2, 3).

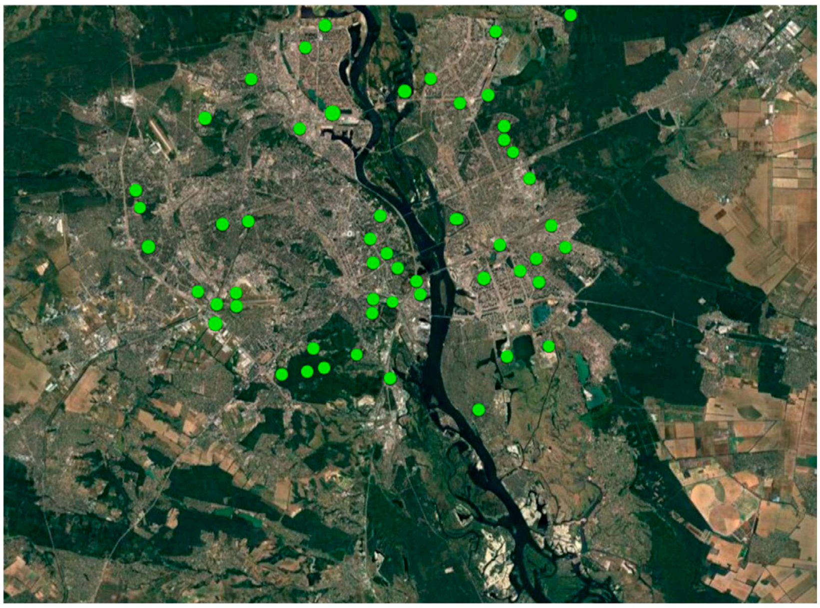


Fig. 3. Air monitoring points in the city of Kyiv

Table 1

Number of monitoring points in Kyiv

Kyiv's district	Existing stations	Active stations
Darnytskyi	58	6
Dniprovskyi	35	8
Desnianskyi	20	2
Holosiyivskyi	47	1
Obolonskyi	40	3
Pecherskyi	25	3
Solomyanskyi	45	4
Podilskyi	38	2
Svyatoshynskyi	45	3
Shevchenkivskyi	45	2
Total	398	54

Therefore, most air quality sensors belong to the class of low-cost sensors (85–90%); high-precision reference sensors from the Kyiv City State Administration (KCSA) account for 10–15% of active stations.

Table 2

Types of sensors in monitoring networks in the city of Kyiv

Platform/network	Basic types of PM2.5 sensors	Number of active stations in Kyiv (percentage)	Equipment type
SaveDnipro / SaveEcoBot citizen stations	Nova Fitness SDS011, Plantower PMS5003/PMS7003, Honeywell HPMA115S0	18–22 (35–40%)	Public low-cost sensors
Kyiv Smart City	Nova Fitness SDS011, Plantower PMS5003/PMS7003	5–7 (10–13%)	Municipal low-cost sensors
Eco City	Nova Fitness SDS011, Plantower PMS5003/PMS7003, Bosch BME280 (additional parameters)	8–10 (15–18%)	Public low-cost sensors
LUN Micro Air	PurpleAir PA-II, Plantower PMS5003/PMS7003	4–6 (8–11%)	Commercial public low-cost sensors
Airly	Plantower PMS5003/PMS7003, Honeywell HPMA115S0	10–12 (18–22%)	Commercial professional low-cost network
Kyiv City State Administration (official stationary posts)	BAM-1020, GRIMM EDM180/EDM164, TEOM 1405	6 (10–11%)	Reference / semi-reference state systems

Table 3

Number of active air quality sensors by equipment type in the capital

Nova Fitness SDS01	Plantower PMS5003/PMS7003/PurpleAir	Honeywell HPMA115S0	Airly proprietary modules	BAM-1020 GRIMM EDM180 TEOM
18–22	22–28	4–6	10–12	6

4. 4. Military load on the capital in 2025: intensity of attacks, destruction, and smoke

Our paper examined the period of shelling of the capital from January to December 2025, which was characterized by a significant number of air attacks on the city's infrastructure, in particular energy facilities.

During the year, the Russian Federation launched 2,556 drones, 122 cruise missiles, and 88 ballistic missiles over Kyiv [28], which led to damage to more than 3,600 infrastructure units. Among the affected facilities were more than 1,500 residential buildings, 119 educational institutions, and 39 healthcare facilities (Fig. 4).

During the year, 171 people died from shelling (Fig. 5), 13 of whom were children, and another 945 residents of the city were injured, including 67 children. In Ukraine, this is 25% of all deaths (out of 682 people) and 21% of injuries (out of 4,443 people) as a result of missile and drone attacks. The deadliest days were July 31–32 deaths, June 17–28, August 28–25; together these days account for half of all deaths for the year. At least two-thirds of the fatalities were caused by missiles, and at least a quarter – by loitering munitions.

Not every missile or drone strike caused large-scale fires or large smoke plumes. However, reports from Kyiv indicated significant smoke in cases where large urban fires occurred as a result of damage to infrastructure and fuel tanks. Sometimes simultaneous fires in several locations combined to create urban-scale smoke, which was reported in the media, for example on June 17, 2025 [29].

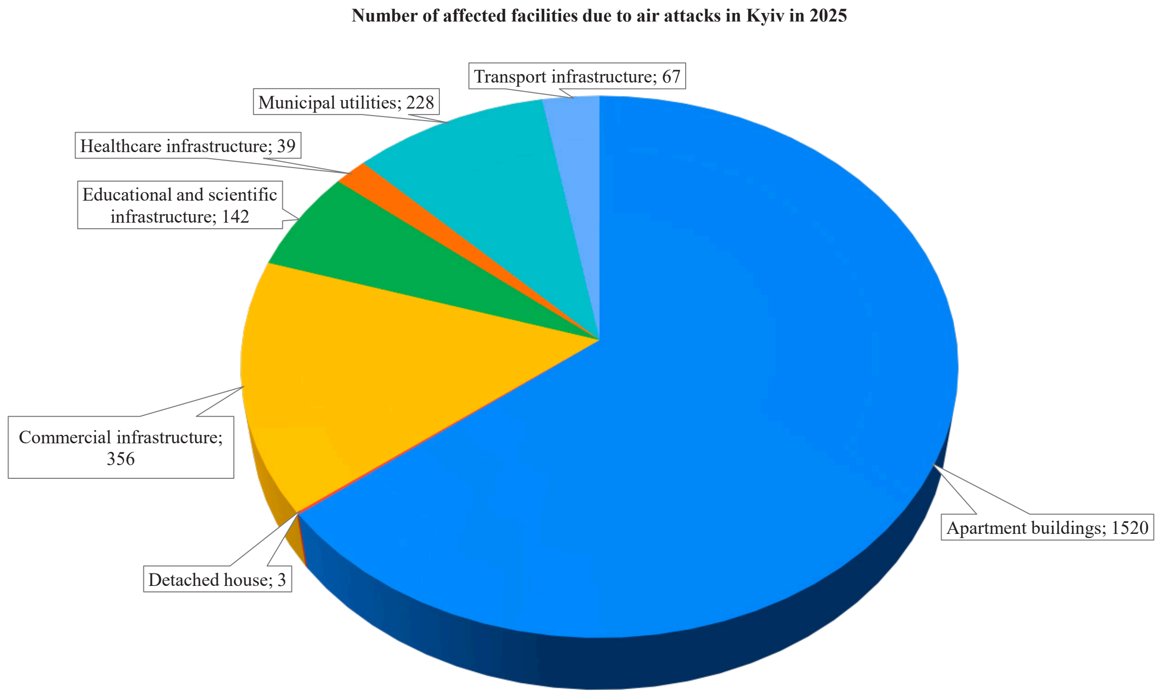


Fig. 4. Number of objects affected by air attacks in Kyiv in 2025

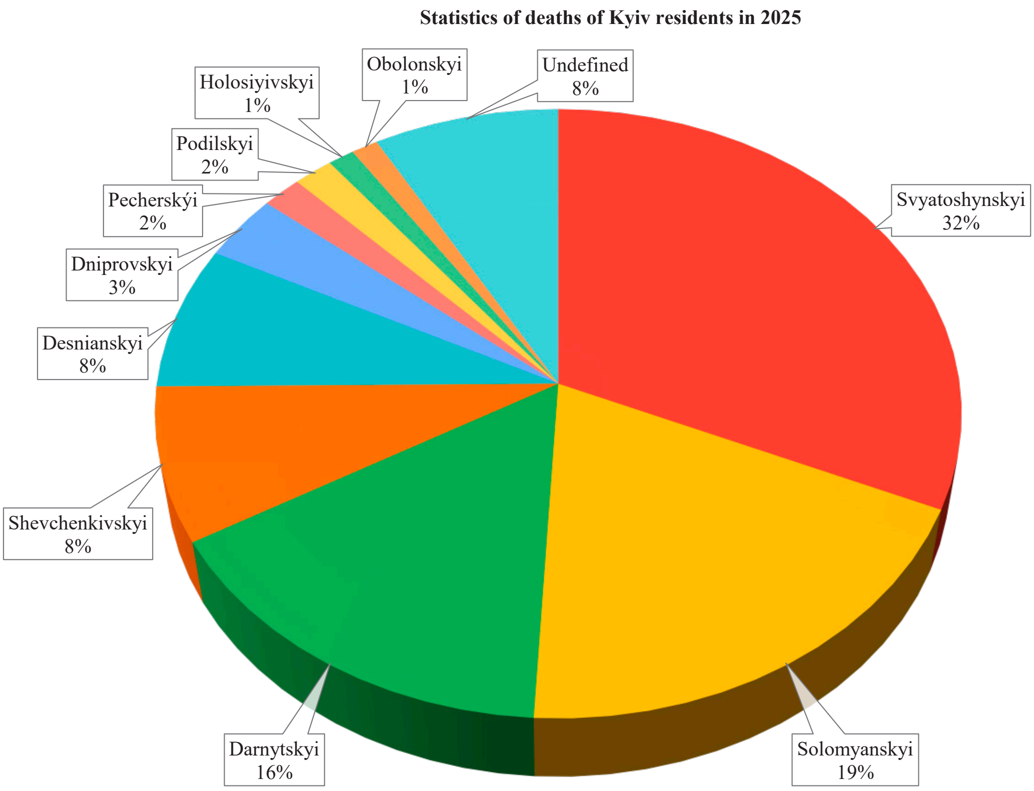


Fig. 5. Number of people killed in Kyiv shelling in 2025

4. 5. Methodology for scenario assessment of the impact of military events on PM2.5 concentrations

To assess the possible impact of military shelling on changes in the concentration of fine particles PM2.5 in the air, a calculation model was built, based on an integral approach taking into account spatial characteristics and events. The purpose of the model is not to establish a direct cause-and-effect relationship between military events and deterioration of air quality but to determine the degree of probable relationship between the nature of the event, the localization of its consequences, and the dynamics of changes in PM2.5 concentrations.

The model is based on the assumption that the impact of military events on the state of atmospheric air can occur both directly and indirectly. The direct impact occurs as a result of local damage, fires, or destruction of infrastructure. The indirect impact is the result of the transfer of combustion products or the result of local atmospheric processes. In this regard, an approach was used for the assessment that involves dividing situations into scenarios of direct and indirect impact.

The initial dataset was formed on the basis of observations and contained information on the date of the event, the administrative district of the city, the actual PM2.5 concentration, the presence or absence of shelling within the city, the confirmed local impact on the district, and the characteristics of the consequences of the event. For the automated combination of atmospheric air monitoring data with spatial parameters, a connection in the date-district format was used. This approach ensured an unambiguous comparison of records from different data sources and allowed us to avoid errors associated with duplication or lack of exact coincidence for individual parameters of the date or territory.

One of the defining stages of the methodology was to take into account the natural spatial heterogeneity of atmospheric air pollution among districts. To this end, an individual baseline level of concentration of fine particles with a diameter of less than 2.5 microns was previously determined for each district, which was used as a background value for further calculations. The use of district baseline values allowed us to avoid distortion of results connected with differences in traffic load, density of buildings, and presence of stationary sources of pollution.

To assess the change of air quality, the relative deviation in the actual PM2.5 indicator from its average background value for the corresponding district was determined. This approach made it possible to assess not the absolute value of the concentration but the degree of its change relative to the characteristic level of pollution for a specific territory. The degree of change in the PM2.5 value was defined as the ratio of difference between the current value of PM2.5 and the average district indicator to the base concentration level

$$\mathrm{PM}_{deviation}=\frac{\mathrm{PM}2.5-\mathrm{PM}2.5_{base}}{\mathrm{PM}2.5_{base}}, \quad (1)$$

where PM2.5 is the actual concentration value on the day of observation, $\mathrm{PM}2.5_{base}$ is the average background level of PM2.5 for the relevant area.

The next stage of the methodology involved formalizing a scenario approach to assessing the possible impact of military events on changes in PM2.5 concentrations. Within the model, the main scenario groups of observations were identified, which reflect different levels of spatial-event connection between military activity and the state of atmospheric air.

The first scenario corresponds to cases of direct possible impact, when the fact of shelling of the city, the presence of confirmed local consequences within a specific area, and a significant excess of the base level of PM2.5 concentration are simultaneously recorded. This combination of conditions is considered the most informative in terms of the potential connection between the event and changes in air quality.

The second scenario describes a possible indirect impact, which is recorded in cases where shelling of the city took place, but local consequences within a specific area were not confirmed, while an increase in PM2.5 concentrations was observed. This scenario may reflect both territorial atmospheric effects and the transfer of combustion products or dust masses from other areas.

The third scenario is used as a control case, characterized by the absence of military events within the city while simultaneously increasing the level of PM2.5. Its inclusion in the model allows us to take into account the impact of alternative factors of atmospheric air pollution not related to military activity.

The fourth scenario corresponds to cases of local impact of military events in the absence of significant deterioration of atmospheric air quality. In such situations, the fact of damage or other type of consequences within the area is recorded; however, changes in PM2.5 concentration do not exceed the established threshold (annual average) value. This scenario describes cases when a potential source of pollution exists; however, its impact on the state of atmospheric air is limited or does not manifest itself in the measured concentrations of fine particles. This may be due to the rapid localization of the consequences, meteorological conditions, low emission intensity, or the time gap between the event and the measurement of the concentration of fine aerosols in the air.

The fifth scenario covers cases where the fact of shelling of the city was not recorded but an increase in PM2.5 concentration above the established threshold (average annual) level was observed. Such factors may include meteorological conditions (temperature inversions, lack of wind, atmospheric stability), seasonal fluctuations in pollution levels, traffic load, industrial emissions, as well as transboundary transport of aerosol particles. Thus, an increase in PM2.5 values in the absence of military events cannot be interpreted as a consequence of shelling and is considered as a background or alternative variation in atmospheric air pollution.

The inclusion of such observations in the model is important as it makes it possible to avoid the erroneous association of air quality changes with military events and provides a basis for comparing different scenarios.

Thus, the full scenario classification of the model includes five groups of observations (Table 4).

Table 4

Main categories of impact

Category	Meaning	How to interpret
Direct possible impact	There was shelling, the area was affected, the PM2.5 concentration increased significantly	The strongest signal impact in the model
Possible indirect impact	There was shelling, but the area has no local confirmed impact, the PM2.5 concentration increased	Possible transport of pollution due to wind or other factors
Bad air without shelling	PM2.5 concentration increased on a day without shelling	Control case: deterioration of air quality due to other reasons
Possible impact without PM2.5 deterioration	The area was affected, but the PM2.5 concentration did not exceed the threshold	The fact of impact is present, but the model does not record a significant deterioration in the PM2.5 value
Control normal day	Without shelling, there is no significant increase in PM2.5 concentration	Baseline control condition

The use of a branched scenario scheme allows for a more complete coverage of possible combinations of events and atmospheric air conditions, as well as increasing the stability of model interpretations by including both “positive” and “negative” examples of impact.

To assess changes in air quality, the PM2.5 deviation index was used, normalized within the range from 0 to 1. The higher the value of this indicator, the more the concentration exceeded the typical level for the corresponding area.

For example, the model parameters are specified in the form of weight coefficients and threshold values, which determine how the integrated index is calculated and how it is interpreted.

To justify the coefficients, the impact scale is conditionally divided into four intervals: 0–0.25 – low impact, 0.25–0.50 – moderate impact, 0.50–0.75 – significant impact, 0.75–1.00 – critical impact. This division makes it possible to interpret the coefficients as equal in strength of the factor’s influence on the result.

The coefficient of 0.3 belongs to the interval of moderate influence. It is chosen not at the lower limit, since the factor already has a noticeable value for the model, but at the same time remains close to the beginning of the second interval. This means that the parameter is taken into account in the calculation but cannot significantly change the final estimate on its own.

The 0.7 coefficient belongs to the interval of significant impact and is located closer to its upper limit. This is justified by the fact that the corresponding parameter has a direct relationship with the result and should have a dominant influence in the model. At the same time, the value does not exceed the critical level limit of 0.75; therefore, the factor is not considered as absolute or the only determining one.

The 0.4 coefficient belongs to the zone of moderate impact but is located above 0.3 since it describes an indirect, but enhanced impact. It can be considered to be an intermediate value between the basic auxiliary impact of 0.3 and the direct significant impact of 0.7. For example, if the pollution source does not directly affect the studied area but the impact can be enhanced by external conditions, in particular the direction and strength of the wind, the coefficient of 0.4 reflects just such a partially indirect impact.

The threshold of 0.15 (15%) is used to determine a significant deterioration in air quality and separate it from minor fluctuations. Setting the threshold value for the indicator of deterioration of atmospheric air quality at a 15% deviation from the baseline level is justified by the need to separate statistically insignificant fluctuations in PM2.5 concentration from potentially significant changes in the state of atmospheric air.

A threshold of 0.15 (15%) was chosen as the boundary separating insignificant deviations from those that may already indicate a real influence of the factor on the result. Smaller threshold values would lead to the model overreacting to natural fluctuations in the data, measurement errors, or rounding. On the other hand, a significantly higher threshold could hide changes that are already of practical importance.

The value of 15% is a compromise between the sensitivity and stability of the model. It is large enough to filter out insignificant fluctuations but, at the same time, allows for timely detection of noticeable changes in the indicators. That is why the 15% threshold was used as a criterion for deciding whether there is a significant influence.

Daily values of PM2.5 fine particulate matter in the air are characterized by natural fluctuations caused by meteorological conditions, diurnal variability of atmospheric circulation, as well as measurement errors and short-term emissions of stationary sources. In this regard, minor deviations from the average level may not reflect the real change in the state of atmospheric air.

Therefore, the threshold value of 0.15 (15%) was chosen as a compromise between the sensitivity of the model and its resistance to data noise.

For the interpretation of the index results, the limits of 0.35 and 0.7 were set, which divide the level of connection into low, medium, and high. Thus, the model parameters play the role of settings that determine the sensitivity and logic of assessing the connection between military events and changes in PM2.5 concentration (Table 5).

To quantify the degree of possible association between military events and changes in PM2.5 concentrations, an integrated association index was introduced, which was calculated taking into account the scenario membership of the observation and the combination of impact factors. In the case of a direct possible impact scenario, the integrated index was defined as a weighted combination of the normalized indicator of PM2.5 concentration change and the local impact coefficient

$$I = 0.7 \cdot PM\_deviation\_score + \\ +0.3 \cdot I\_impact, \quad (2)$$

where I is the integrated index of possible correlation,

PM_deviation_score is the normalized deviation index of PM2.5 concentration,

I_impact is the event intensity coefficient determined based on the reference system of parameters.

For the indirect possible impact scenario, a simplified form of assessment was used

$$I = 0.4 \cdot PM\_deviation\_score. \quad (3)$$

This approach was based on the assumption that changes in PM2.5 concentrations could be related not only to local sources of pollutants but to regional atmospheric processes as well. Possible mechanisms included the transport of combustion products by air currents, the secondary formation of aerosol particles, the spread of smoke from fires, or the redistribution of fine particles within the urban environment. In this case, the PM2.5 indicator was used as the only indicator of a possible indirect effect, but its contribution was further reduced due to a smaller weighting factor.

The resulting integrated index values were used to further systematize the level of probable connection between events and changes in PM2.5. Three levels of interpretation were distinguished (Table 6).

This gradation makes it possible to move from a continuous numerical assessment to an interpreted qualitative scale, convenient for further analysis and visualization of the results.

To take into account different intensities of events in the model, a separate reference block of impact coefficients was used (Table 7). The values of the coefficients were formed taking into account the potential ability of the event to generate secondary aerosol load. The minimum values were given to events without confirmed consequences, and the maximum values were assigned to cases of damage to industrial facilities and large-scale fires. Intermediate scenarios associated with explosions, drone attacks, missile strikes and combined types of damage were also taken into account.

The final stage of the methodology involved summarizing the results in the form of integrated indicators. These indicators included the total number of observations, the number of days with shelling, the number of areas with confirmed impact, the number of cases of air quality deterioration, and the average values of the correlation index. The results were used for further analysis of patterns in the changes in PM2.5 concentration during military events and assessment of the potential impact of such events on the state of atmospheric air.

As a result, the model forms an integrated numerical index that reflects the probable degree of connection between military events and changes in PM2.5 concentration within individual areas. Based on this index, each case is assigned a qualitative interpretation of the level of connection (low, medium, or high), which makes it possible to summarize the results of a large array of observations and identify potentially significant situations for further analysis.

Table 5

Values of the parameters in a given model and their role

Parameter	Value	Role in the model
Weight PM_deviation_score for direct impact	0.7	The main part of the index for direct impact depends on the growth of PM2.5
Weight Impact_index for direct impact	0.3	Adds weight to the type of impact: fire, infrastructure, industrial facility, etc.
Weight Indirect impact	0.4	Reduces the index if the area is not directly affected
Minimum PM2.5 increase	0.15	Threshold +15%, after which the air is considered to have deteriorated
Medium linkage threshold	0.35	Border between low and medium level
High linkage threshold	0.7	Border between medium and high level

Table 6

Categories of levels of probable connection

Association level	Low	Medium	High
Value	from 0 to 0.35	from 0.35 to 0.7	from 0.7 to 1.0

Table 7

Coefficients of impact of military events on districts

Impact type	Impact index	Explanation
none	0.00	no confirmed local impact
debris	0.25	fragments / local damage
explosion	0.40	explosion without specified consequences
drone	0.45	attack without confirmed strong local impact
missile	0.55	missile strike / potentially stronger type of attack
combined	0.65	combined attack, high risk, but not maximum without consequences
fire	0.75	fire, direct risk of smoke and PM2.5
infrastructure_damage	0.70	infrastructure damage
industrial_object_damage	0.90	industrial damage, highest risk of pollution
residential_damage	0.55	residential destruction/dust
unknown	0.30	impact is present but type unknown
other	0.30	other type of impact
fire + debris	0.85	fire + debris
combined+fire	0.95	combined attack + fire
fire + residential_damage	0.90	fire + destruction of residential buildings
combined + infrastructure_damage	1.00	combined attack + damage to infrastructure
debris + residential_damage	0.65	debris + destruction of residential buildings
fire + infrastructure_damage	0.95	fire + damage to infrastructure

5. Results of research on the assessment of changes in PM2.5 concentrations in Kyiv during wartime

5. 1. Assessment of the state of atmospheric air in the districts of Kyiv during 2025

The results of monitoring observations of the state of air, in particular the concentration of fine dust PM2.5, in the districts of the capital in 2025 demonstrate significant spatial heterogeneity of pollution (Fig. 6). First of all, this unevenness is due to the anthropogenic urban "peaceful" load, which includes transport load, density of urban development, industrial production, as well as the features of the natural relief of the territory.

The average annual values of PM2.5 characterize the general situation regarding the state of air due to dispersed pollution in the districts. However, the content of aerosols in the air is very dynamic and related to the seasons. Fig. 7 shows the nature of changes in the PM2.5 indicator during the year in 10 districts of the city.

In almost all districts of the city, there is an increase in concentrations in the cold season (autumn, winter), which is primarily due to the heating season and, accordingly, an increase in emissions from thermal power plants and boiler houses. In addition, meteorological phenomena have a negative impact, in particular temperature inversion, which leads to less intense vertical air mixing, a decrease in the rate of dispersion of pollutants and, as a result, to a significant accumulation of aerosols in the surface layer of the atmosphere.

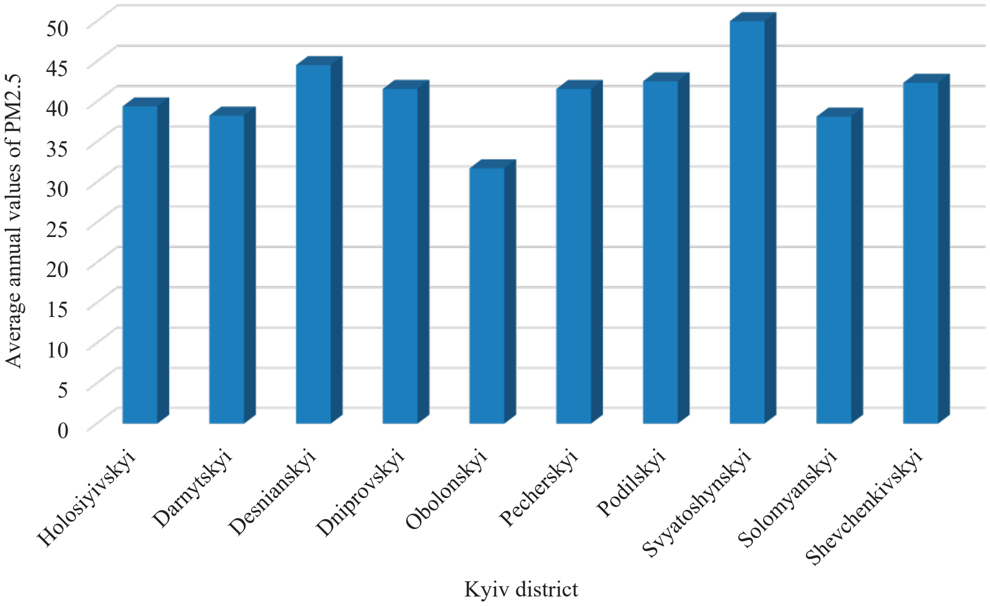
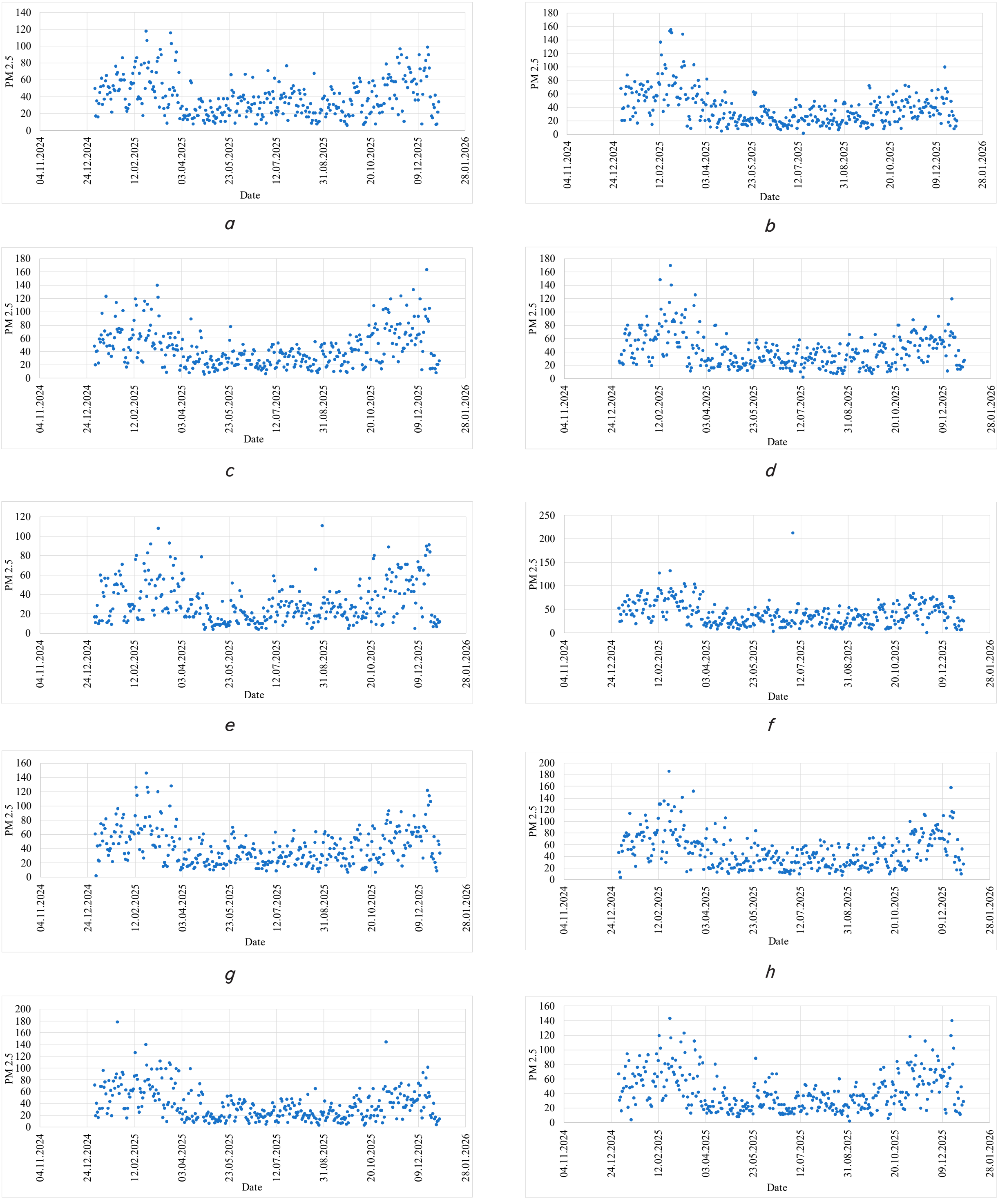


Fig. 6. Average annual values of PM2.5 fine dust concentration in Kyiv districts for 2025



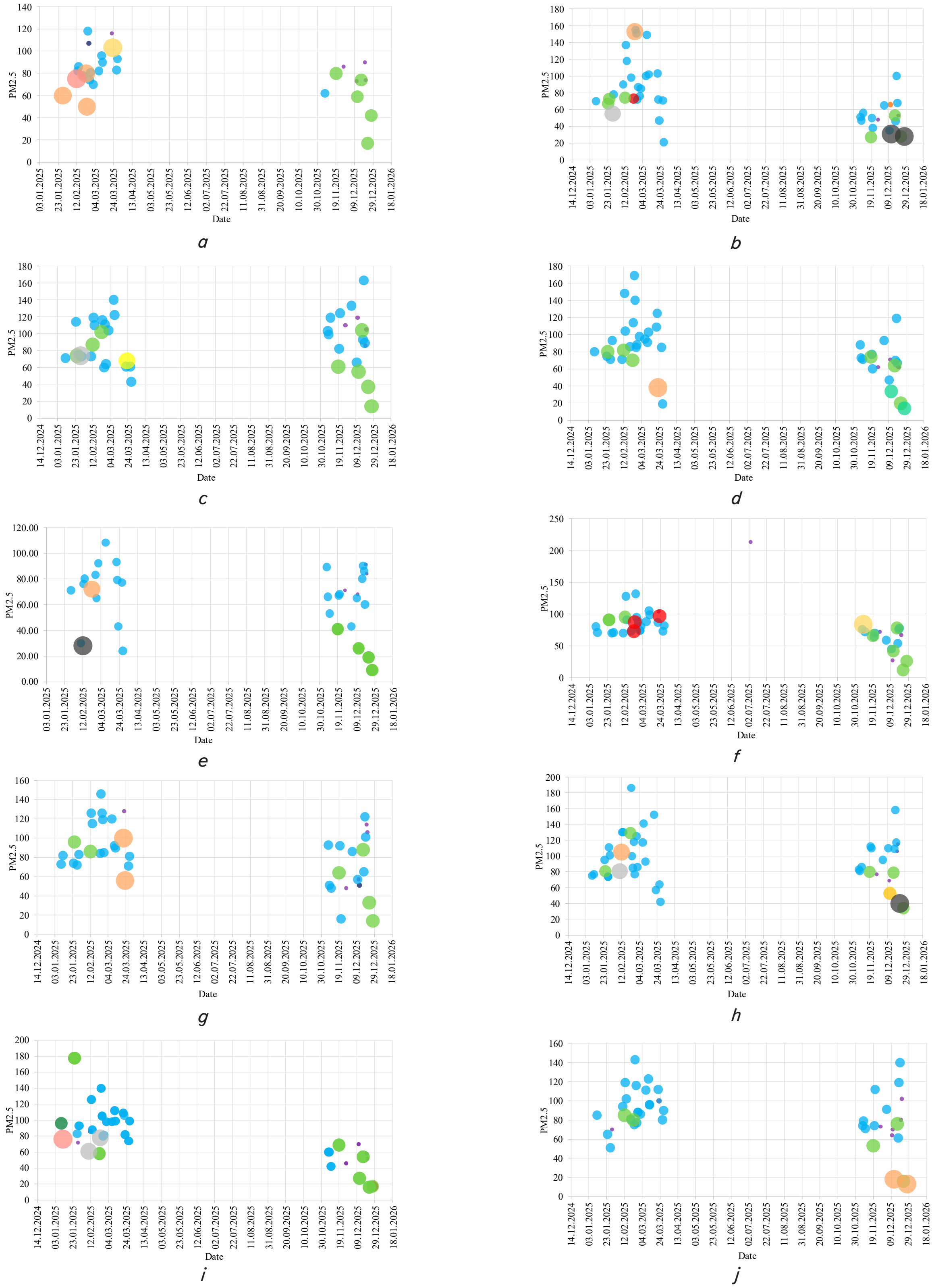
a *b* *c* *d* *e* *f* *g* *h* *i* *j*

Fig. 7. The nature of changes in PM2.5 concentration in the administrative districts of Kyiv during 2025: *a* – Holosiyivskyi; *b* – Darnytskyi; *c* – Desnianskyi; *d* – Dniprovskyi; *e* – Obolonskyi; *f* – Pecherskyi; *g* – Podilskyi; *h* – Svyatoshynskyi; *i* – Solomyanskyi; *j* – Shevchenkivskyi

5. 2. Spatial-temporal generation of atmospheric air pollution in Kyiv taking into account massive shelling

As noted above, 2025 was marked by powerful military pressure on Kyiv due to periodic air attacks by the aggressor, which were accompanied by extensive destruction of infrastructure, residential buildings of the capital, and human casualties. The destruction of industrial and municipal facilities in the city was accompanied by significant local pollution of the affected areas.

Fig. 8 shows a comprehensive analysis of the situation by district, which includes the dates and nature of the shelling, their consequences in terms of destruction and associated manifestations, as well as the concentration of PM2.5 fine aerosols in the air. The diameter of the circles indicates the scale of the impact of military events on districts in accordance with the adopted coefficients (Table 7).



a *b* *c* *d* *e* *f* *g* *h* *i* *j*

Fig. 8. Situations by city districts in 2025, taking into account the date and nature of the shelling, their consequences in terms of destruction and accompanying manifestations, as well as the concentration of fine aerosols in the air: *a* — Holosiyivskyi; *b* — Darnytskyi; *c* — Desnianskyi; *d* — Dniprovskyi; *e* — Obolonskyi; *f* — Pecherskyi; *g* — Podilskyi; *h* — Svyatoshynskyi; *i* — Solomyanskyi; *j* — Shevchenkivskyi; ● — no impact; ● — destruction of buildings/dust; ● — fire and debris; ● — explosion without specifying the consequences; ● — damage to infrastructure; ● — debris/local damage; ● — combined attack and fire; ● — combined attack; ● — missile strike; ● — fire; ● — unknown type; ● — other; ● — type of attack without confirmed strong local consequences; ● — combined attack and damage to infrastructure; ● — fire and damage to infrastructure; ● — fire and destruction of residential buildings; ● — debris and destruction of residential buildings; ● — damage to an industrial facility

The diagrams above allow us to trace the temporal dynamics of atmospheric air pollution and correlate them with the consequences of air attacks.

Analysis of the plots above reveals that in all the studied districts there are significant fluctuations in PM2.5 concentrations, which have a pronounced uneven nature. The highest values of fine dust were recorded during periods of massive, combined attacks and fires caused by damage to residential, energy, or industrial infrastructure against the background of seasonal atmospheric patterns. In most districts, PM2.5 concentrations on such days exceeded background values by several times, which indicates a significant impact of combustion processes, destruction of building materials, and secondary dust pollution.

5. 3. Statistical analysis of scenarios of the impact of military events on atmospheric air quality

Based on the generalization of our results in the form of integrated indicators, the patterns of changes in PM2.5 concentration during massive shelling of the city and the assessment of the potential impact of such events on the state of atmospheric air were determined. The potential impact of military events was carried out using the methodology described above. A fragment of the data analysis is shown in Fig. 9.

Based on the calculations, generalized statistics of the distribution of observations between scenario categories were formed in accordance with the input impact categories (Table 4) for 2025. The results of statistical data processing are given in Table 8 and Fig. 10.

Our model does not determine the causality of changes but rather performs the function of a structured assessment and classification of cases according to the degree of probable impact of military events on the state of the city's atmospheric air.

Table 8

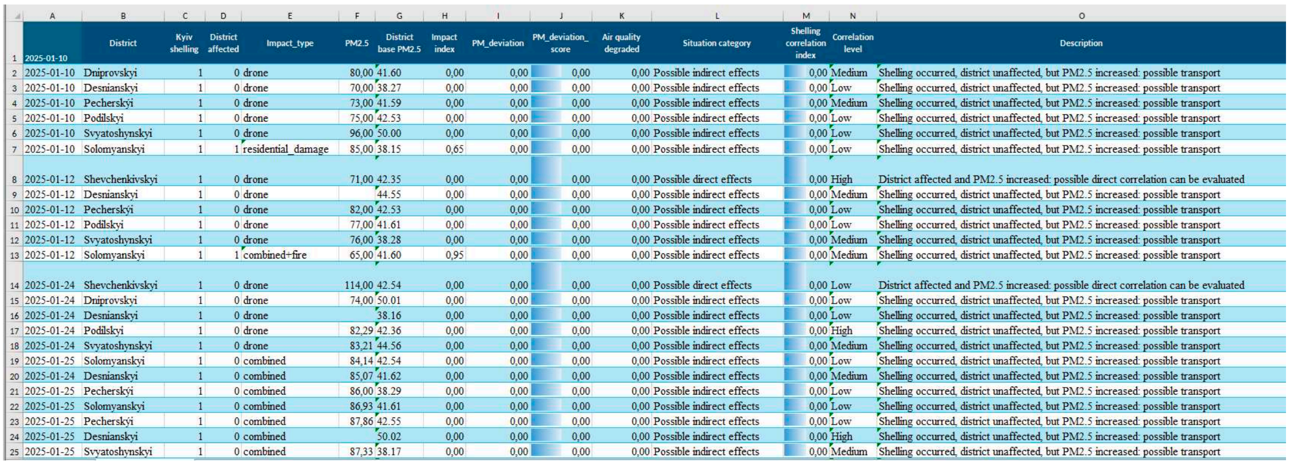
Summary indicators of the model for assessing the relationship between military events and PM2.5 concentration in Kyiv for 2025

Category	Number	Average index
Direct possible impact	28	0.79
Possible indirect impact	340	0.34
Bad air without shelling	43	0.00
There was an impact, but PM2.5 did not worsen	11	0.00
Control normal day	2	0.00

6. Discussion of results based on the scenario analysis of changes in the air quality in the capital

The anthropogenic load on fine aerosols (PM2.5) in the air of Kyiv in 2025 was felt in all administrative districts of the city without exception [19, 20]. However, the average annual PM2.5 concentrations in the districts fluctuate within 30–50 $\mu g/m^3$, depending on the specificity of district structure (Fig. 6).

The highest average annual content of fine aerosols is observed in the Svyatoshynskyi district. The PM 2.5 concentration for this district is 49.99 $\mu g/m^3$, and this is the maximum (worst) indicator among all districts of the capital. The high concentration of particles in the air with a diameter of less than 2.5 μm is associated with the high load of highways in the district, as well as with a significant number of industrial zones.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	2025-01-10	District	Kyiv shelling	District affected	Impact_type	PM2.5	District base PM2.5	Impact index	PM_deviation	PM_deviation_ score	Air quality degraded	Situation category	Shelling correlation index	Correlation level	Description
2	2025-01-10	Dniprovskyi	1	0	drone	80,00	41.60	0,00	0,00	0,00	0,00	Possible indirect effects	0,00	Medium	Shelling occurred, district unaffected, but PM2.5 increased: possible transport
3	2025-01-10	Desnianskyi	1	0	drone	70,00	38.27	0,00	0,00	0,00	0,00	Possible indirect effects	0,00	Low	Shelling occurred, district unaffected, but PM2.5 increased: possible transport
4	2025-01-10	Pecherskyi	1	0	drone	73,00	41.59	0,00	0,00	0,00	0,00	Possible indirect effects	0,00	Medium	Shelling occurred, district unaffected, but PM2.5 increased: possible transport
5	2025-01-10	Podilskyi	1	0	drone	75,00	42.53	0,00	0,00	0,00	0,00	Possible indirect effects	0,00	Low	Shelling occurred, district unaffected, but PM2.5 increased: possible transport
6	2025-01-10	Svyatoshynskyi	1	0	drone	96,00	50.00	0,00	0,00	0,00	0,00	Possible indirect effects	0,00	Low	Shelling occurred, district unaffected, but PM2.5 increased: possible transport
7	2025-01-10	Solomyanskyi	1	1	residential_damage	85,00	38.15	0,65	0,00	0,00	0,00	Possible indirect effects	0,00	Low	Shelling occurred, district unaffected, but PM2.5 increased: possible transport
8	2025-01-12	Shevchenkivskyi	1	0	drone	71,00	42.35	0,00	0,00	0,00	0,00	Possible direct effects	0,00	High	District affected and PM2.5 increased: possible direct correlation can be evaluated
9	2025-01-12	Desnianskyi	1	0	drone		44.55	0,00	0,00	0,00	0,00	Possible indirect effects	0,00	Medium	Shelling occurred, district unaffected, but PM2.5 increased: possible transport
10	2025-01-12	Pecherskyi	1	0	drone	82,00	42.53	0,00	0,00	0,00	0,00	Possible indirect effects	0,00	Low	Shelling occurred, district unaffected, but PM2.5 increased: possible transport
11	2025-01-12	Podilskyi	1	0	drone	77,00	41.61	0,00	0,00	0,00	0,00	Possible indirect effects	0,00	Low	Shelling occurred, district unaffected, but PM2.5 increased: possible transport
12	2025-01-12	Svyatoshynskyi	1	0	drone	76,00	38.28	0,00	0,00	0,00	0,00	Possible indirect effects	0,00	Medium	Shelling occurred, district unaffected, but PM2.5 increased: possible transport
13	2025-01-12	Solomyanskyi	1	1	combined+fire	65,00	41.60	0,95	0,00	0,00	0,00	Possible indirect effects	0,00	Medium	Shelling occurred, district unaffected, but PM2.5 increased: possible transport
14	2025-01-24	Shevchenkivskyi	1	0	drone	114,00	42.54	0,00	0,00	0,00	0,00	Possible direct effects	0,00	Low	District affected and PM2.5 increased: possible direct correlation can be evaluated
15	2025-01-24	Dniprovskyi	1	0	drone	74,00	50.01	0,00	0,00	0,00	0,00	Possible indirect effects	0,00	Low	Shelling occurred, district unaffected, but PM2.5 increased: possible transport
16	2025-01-24	Desnianskyi	1	0	drone		38.16	0,00	0,00	0,00	0,00	Possible indirect effects	0,00	Low	Shelling occurred, district unaffected, but PM2.5 increased: possible transport
17	2025-01-24	Podilskyi	1	0	drone	82,29	42.36	0,00	0,00	0,00	0,00	Possible indirect effects	0,00	High	Shelling occurred, district unaffected, but PM2.5 increased: possible transport
18	2025-01-24	Svyatoshynskyi	1	0	drone	83,21	44.56	0,00	0,00	0,00	0,00	Possible indirect effects	0,00	Medium	Shelling occurred, district unaffected, but PM2.5 increased: possible transport
19	2025-01-25	Solomyanskyi	1	0	combined	84,14	42.54	0,00	0,00	0,00	0,00	Possible indirect effects	0,00	Low	Shelling occurred, district unaffected, but PM2.5 increased: possible transport
20	2025-01-24	Desnianskyi	1	0	combined	85,07	41.62	0,00	0,00	0,00	0,00	Possible indirect effects	0,00	Medium	Shelling occurred, district unaffected, but PM2.5 increased: possible transport
21	2025-01-25	Pecherskyi	1	0	combined	86,00	38.29	0,00	0,00	0,00	0,00	Possible indirect effects	0,00	Low	Shelling occurred, district unaffected, but PM2.5 increased: possible transport
22	2025-01-25	Solomyanskyi	1	0	combined	86,93	41.61	0,00	0,00	0,00	0,00	Possible indirect effects	0,00	Low	Shelling occurred, district unaffected, but PM2.5 increased: possible transport
23	2025-01-25	Pecherskyi	1	0	combined	87,86	42.55	0,00	0,00	0,00	0,00	Possible indirect effects	0,00	Low	Shelling occurred, district unaffected, but PM2.5 increased: possible transport
24	2025-01-25	Desnianskyi	1	0	combined		50.02	0,00	0,00	0,00	0,00	Possible indirect effects	0,00	High	Shelling occurred, district unaffected, but PM2.5 increased: possible transport
25	2025-01-25	Svyatoshynskyi	1	0	combined	87,33	38.17	0,00	0,00	0,00	0,00	Possible indirect effects	0,00	Medium	Shelling occurred, district unaffected, but PM2.5 increased: possible transport

Fig. 9. Assessment of massive shelling on the state of Kyiv's atmospheric air in 2025

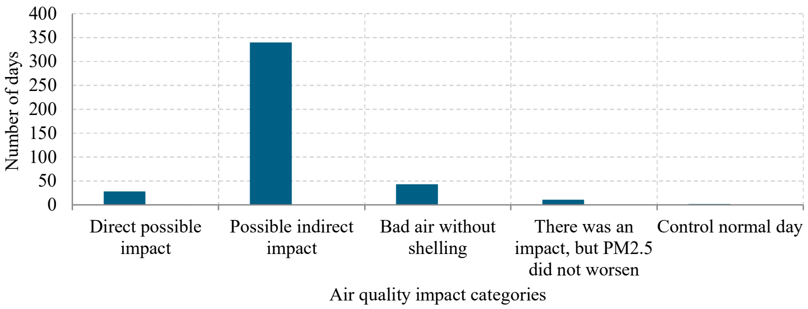


Fig. 10. Summarizing the results of scenario analysis for changes in PM2.5 concentration

The second place in terms of pollution level is occupied by Desnianskyi district with an indicator of 44.55 μg/m^3. High values are also characteristic of Podilskyi (42.53 μg/m^3), Shevchenkivskyi (42.35 μg/m^3), Dniprovskyi (41.60 μg/m^3), and Pecherskyi (41.59 μg/m^3) districts, which indicates a significant anthropogenic load in the central and densely populated parts of the city.

The average PM2.5 level in Holosiyivskyi district is 39.42 μg/m^3, which is lower than the citywide average, but still indicates increased pollution. Similar values are typical for Darnytskyi (38.27 μg/m^3) and Solomyanskyi (38.15 μg/m^3) districts.

The lowest pollution level was recorded in Obolonskyi district – 31.72 μg/m^3. This can be explained by more favorable ventilation conditions of the flat area, lower concentration of emission sources, and a significant share of forest-park zones.

In general, the average annual PM2.5 value in Kyiv is approximately 40.62 μg/m^3, which significantly exceeds the standards recommended by the World Health Organization, according to which the average annual PM2.5 concentration should not exceed 5 μg/m^3. This indicates a high level of risk to public health, in particular regarding the development of cardiovascular, respiratory, and oncological diseases.

Average annual indicators allow us to assess the overall level of constant atmospheric air pollution. In contrast, analysis of annual dynamics makes it possible to identify periods of maximum environmental risk, seasonal patterns, and the specific impact of other factors on air quality (Fig. 7).

Changes in PM2.5 concentrations during the year have a pronounced seasonal character.

All regions are characterized by a common pattern – an increase in PM2.5 concentrations at the beginning and end of the year and a decrease in pollution levels in the warm period. The nature of the curves shown in Fig. 7 forms a typical U-shaped seasonal dependence.

In the winter-spring period (the first 50–80 days of the year), PM2.5 concentrations often exceed 60–100 μg/m^3, and individual peak values reach 140–180 μg/m^3, which is explained by the presence of the heating season, adverse meteorological conditions, etc.

In the summer period (approximately 100–270 days of the year), a noticeable decrease in PM2.5 concentrations is observed in all regions. Most values at this time are within 10–40 μg/m^3, which is explained by intensive mixing of the verified masses, respectively, more active dispersion of aerosols, lack of heating, etc. However, from time to time, spikes in aerosol concentrations in the air are observed, which are caused by dust phenomena, summer fires, and active traffic.

At the end of the year (after 280–300 days), a steady increase in PM2.5 concentration is again observed in almost all districts, due to the next start of the heating season and a natural change in weather conditions.

As can be seen from Fig. 7, among the districts of Kyiv, the highest and most unstable concentrations are characteristic of Svyatoshynskyi, Desnianskyi, Podilskyi, Shevchenkivskyi, and Pecherskyi districts. In Svyatoshynskyi district, some of the highest peaks exceeding 180 μg/m^3 were recorded in 2025. Pecherskyi district demonstrates individual extreme values – over 200 μg/m^3, which may be due to local short-term crises and uneven terrain. Desnianskyi and Shevchenkivskyi districts are also characterized by a significant amplitude of seasonal fluctuations.

Obolonskyi district is characterized by a relatively lower overall level of PM2.5 and a smaller number of extreme peaks, which is explained by the flat relief, a small number of industrial zones in the district. Holosiyivskyi, Darnytskyi, and Solomyanskyi districts occupy an intermediate position, demonstrating a typical seasonal pattern without an excessive number of critical excesses.

Thus, atmospheric air pollution in Kyiv is characterized by spatial and temporal (seasonal) heterogeneity, which can be complicated by urban, technogenic, and military events.

Under martial law conditions, volleys of substances into the air as a result of the destruction of objects due to emergency emissions and secondary dust rising from damaged areas are extremely dangerous for public health [26, 27].

As shown in Fig. 8, significant fluctuations in PM2.5 concentrations are observed in all districts of Kyiv, which have a pronounced uneven nature. The highest values of fine dust fractions were recorded during periods of massive, combined attacks and fires caused by damage to residential, energy, or industrial infrastructure. In most districts, PM2.5 concentrations during these periods exceeded background values by several times, which indicates a significant impact of combustion processes, destruction of building structures and secondary dust pollution.

For the Holosiyivskyi district, elevated PM2.5 concentrations in two time intervals are characteristic, which are associated with separate waves of intense attacks. At the same time, there is a significant spread of values, which is explained by the different intensity of fires and the meteorological conditions of the dispersion of impurities at that time. During the attacks at the beginning of the year, PM 2.5 concentrations reached 120 μg/m^3, and in November–December this indicator was at the level of 90 μg/m^3. A similar trend is observed for the Darnitsa district where individual peak concentrations of more than 150–170 μg/m^3 are recorded.

Desnianskyi and Dniprovskyi districts are also characterized by high levels of atmospheric air pollution, but their nature is more heterogeneous. In particular, in some cases, sharp jumps in concentrations were recorded during the attacks. This may be due to the difference in the types of affected objects, the scale of fires and the density of development of the territory. Thus, at the beginning of the year after the shelling, the concentration of PM2.5 in Desnianskyi district reached 150 μg/m^3, and in Dniprovskyi district – 170 μg/m^3. During the December attacks, the concentrations of fine aerosols were 170 μg/m^3 and 120 μg/m^3, respectively.

Obolonskyi and Podilskyi districts are characterized by significant fluctuations in PM2.5 concentrations. In these districts, both cases of sharp deterioration in air quality and events without significant excess of concentrations are observed. The consequences of shelling at the beginning and end of the year for the Obolon district were characterized by PM2.5 concentrations of 100 μg/m^3 and 90 μg/m^3, respectively, and for the Podil district – 150 μg/m^3 and 130 μg/m^3.

The Pechersk district is characterized by a relatively smaller number of extreme PM2.5 values (80–140 μg/m^3); however, the state recording graph contains some abnormally high indicators, which may be related to the transfer of pollution from neighboring districts.

In the Svyatoshynskyi and Solomyanskyi districts, which were most frequently attacked in 2025, clear periods of increased PM2.5 concentrations are recorded, which is associated with the damage to industrial facilities. These areas are characterized by maximum post-shelling concentrations of fine aerosols. At the beginning of the year, indicators of 190 μg/m^3 were recorded in the Svyatoshynskyi district, and 180 μg/m^3 in the Solomyanskyi district. At the end of the year, the values were 160 μg/m^3 and 80 μg/m^3, respectively.

The Shevchenkivskyi district demonstrates one of the most amplitude patterns of changes in PM2.5 concentrations. Fig. 8 shows almost the same values of PM2.5 concentrations after massive shelling, at the level of 150 μg/m^3, which is again associated with the damage to industrial facilities.

The general results of the city's air quality by PM2.5 concentration, formed under the influence of military events, demonstrate the formation of short-term periods of extreme air pollution. The change in PM2.5 concentrations is spatially heterogeneous and depends on the type of affected infrastructure, the scale of fires, building density, and meteorological conditions.

Similar monitoring observations for the city of Kyiv were conducted by other authors, but for a monthly interval (June 2025) [13]. The authors also confirm that the PM2.5 indicator is a reliable indicator of air quality, reflecting long-term trends and short-term amplitude episodes. The work showed that prevailing winds play a decisive role in the spatial development of smoke plumes associated with fires. It was found that short-term episodes (up to 8–9 hours) increase the average daily PM2.5 concentrations above the WHO recommended values.

The results of our scenario analysis indicate the presence of a relationship between massive air attacks and changes in fine dust concentrations PM2.5 in the city of Kyiv during 2025. Based on the integral assessment, the observations were classified according to the degree of potential impact of military events on the state of atmospheric air. Our approach allowed us to systematize significant and identify the most characteristic scenarios for the formation of periods of increased pollution. A fragment of the analysis of the monitoring data set is shown in Fig. 9. The fragment demonstrates examples of assessing the impact of air attacks on PM2.5 concentrations in different areas of the city. The results indicate that after individual attacks, a significant deterioration in atmospheric air quality was observed, which was accompanied by a sharp increase in fine dust concentrations. Such changes may be associated with large-scale fires, destruction of building structures, burning of fuel and lubricants, as well as secondary dust pollution of territories.

As can be seen from the results of statistical data processing (Table 8), the largest share of observations was in the category "Possible indirect impact". This category includes 340 cases with an average index of 0.34. That is, in most cases, an indirect connection was observed between military events and deterioration of air quality, which was formed as a result of the transfer of pollution by air masses, the cumulative urban load, or the impact of several emission sources simultaneously.

The category "Direct possible impact" included 28 cases and was characterized by the highest average index – 0.79. This indicates a high probability of direct impact of military events on the deterioration of the atmospheric air in the relevant areas of the city. It was this category that was characterized by maximum and localized increases in PM2.5 concentrations.

The categories "Bad air without shelling" and "There was an impact, but PM2.5 did not deteriorate" were characterized by zero average indices. These categories reflect situations when increased PM2.5 concentrations were formed without a direct connection with military events or, conversely, military impact was not accompanied by a statistically significant deterioration in air quality. Such cases confirm the complex multifactorial nature of the formation of aerosol pollution in a metropolis, where meteorological conditions and background anthropogenic sources of pollution play a significant role.

The smallest number of observations was attributed to the category "Control normal day". And these are only 2 cases that mark days without shelling with a simultaneous lack of an increase in PM2.5 concentration during the day.

The summary of results from scenario analysis, shown in Fig. 10, confirms the dominance of indirect impact scenarios and the presence of individual cases with a high probability of direct military impact on PM2.5 concentrations.

Our model does not establish a direct cause-and-effect relationship between military events and changes in atmospheric air quality. However, it allows for a structured assessment and classification of events by the degree of potential impact, which is important for further environmental research and monitoring systems under martial law.

The fundamental difference of the proposed scenario approach is that it combines not only the spatiotemporal change in PM2.5 concentrations but also the event context: the fact of shelling, the localization of consequences, and the presence of a confirmed impact on a specific area. Traditional analysis of spatiotemporal series makes it possible to establish when and where the increase in pollutant concentration occurred but does not take into account the type of event that could have caused this increase. In the proposed model, each observation is considered to be a combination of three components: time, territory, and the nature of the military event. This makes it possible to distinguish between scenarios of direct possible impact, indirect impact, background changes, and control cases.

The implementation of our study had certain limitations from the very beginning, related to the technical capabilities of PM2.5 concentration monitoring sensors, namely measurement accuracy, sensitivity, and location in the city.

The disadvantages of the methodology include the lack of a detailed analysis of current meteorological conditions and their linking to the dynamics of aerosol dispersion.

Further studies could take into account the meteorological situation in the methodology, which is associated with seasonal variability, consideration of the current concentration of fine aerosols in the air in comparison with the average background seasonal and monthly values. Another area for further research may be the construction of aerosol distribution models taking into account wind rose, terrain relief, and urban density.

7. Conclusions

1. The results of our study indicate that the state of the atmospheric air of Kyiv in 2025 was characterized by high concentrations of fine aerosols PM2.5 and significant territorial heterogeneity. The maximum values of the indicator at the level of 170–190 μg/m^3 were recorded in districts characterized by significant anthropogenic development of the territory and a significant share of industrial zones: Svyatoshynskyi and Desnianskyi districts. In all districts of the city, periods of a sharp increase in the concentrations of fine aerosols were recorded throughout the year, especially in the autumn-winter season, which is associated with the heating season. The seasonal dynamics of concentrations corresponded to a typical U-shaped dependence with peaks in the cold period of the year.

2. We have established that military load is an additional factor in the generation of aerosol pollution in the city. On the days of massive attacks, PM2.5 concentrations in the capital's districts exceeded the average annual background values by 3–5 times. The most significant changes in air quality were associated with large-scale fires and the destruction of infrastructure, in particular energy-related. It was established that even in the absence of local damage to the district, an increase in PM2.5 concentrations is possible due to the transfer of combustion products.

3. Statistical evaluation of the scenarios of the impact of military events has made it possible to identify the main categories of atmospheric air pollution formation. The highest values of the integrated index were characteristic of direct impact scenarios, while indirect impact scenarios formed the largest number of observations. The predominance of indirect impact cases indicates the important role of atmospheric transfer of combustion products. The proposed integrated index provided the possibility for quantitatively assessing the level of potential interrelationship between military events and changes in PM2.5 concentrations. Our approach allows the results to be used for operational environmental monitoring and risk assessment.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

Authors' contributions

Viacheslav Hnatiuk: Visualization, Investigation; **Anastasiia Skliarova**: Data curation, Writing – original draft; **Yuliia Kyrylenko:** Methodology, Software; Dmytro Sidorov: Resources, Formal analysis; **Tetyana Shabliy:** Conceptualization, Validation, Project administration, Writing – review & editing, Supervision.

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