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DETERMINING LOCATIONS FOR DEVELOPING AN AIR QUALITY MONITORING SYSTEM IN A RAPIDLY DEVELOPING URBAN AREA (A CASE STUDY OF THE CITY OF KYIV)

A large population characterizes the modern development of society, and consequently, increasing economic and energy demands. Significant emissions of industrial pollutants into the atmosphere, vehicle exhaust, and the use of chemical substances in daily life contribute to the deterioration of air quality and exacerbate climate change.
In addition, Ukraine has faced unprecedented damage to atmospheric air quality caused by the large-scale armed aggression. Kyiv ranks among the most polluted cities in the country and occasionally appears at the top of global air pollution rankings. For instance, in 2023, the average annual concentrations of sulfur dioxide, nitrogen dioxide, formaldehyde, and phenol in Kyiv exceeded the average daily maximum permissible concentrations by 1.5 to 2.5 times the recommended levels.
The Central Geophysical Observatory, which monitors the city's air quality and holds the most detailed information on the subject, urgently requires modernization. This includes expanding the monitoring network and enhancing its technical and informational infrastructure.
At the same time, the capital is a leader in urban digitalization not only in Ukraine but also across Europe. Against this backdrop, the renewal and expansion of Kyiv's environmental monitoring system, particularly in terms of air quality, must become a priority.
Additionally, the connection between the capital and the surrounding region is continuously intensifying, leading to increased anthropogenic pressure on air quality from transport. This paper presents the structure of the Kyiv agglomeration. It proposes a project for the tentative placement of air quality monitoring system locations in the city of Kyiv, taking into account the locations of major development clusters within the agglomeration.

Keywords: *environmental monitoring system, pollutant emissions*, *air quality, urban area*

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Problem Statement

Air quality monitoring involves the systematic observation, collection, analysis, and evaluation of data regarding the state of the atmosphere and the factors that influence it. It also includes forecasting air quality changes and developing scientifically grounded recommendations to inform management decisions that aim to ensure environmental safety, preserve the natural environment, and protect public health.

For a metropolis like Kyiv, air quality monitoring is a critically important control system, especially given the increasing frequency with which the capital appears in the top rankings of cities with the most polluted air in the world [1, 2, 3] (Fig. 1). According to the globally recognized IQAir service [3], on September 22, 2024, the concentration of fine particulate matter (PM2.5) in Kyiv exceeded the WHO's annual guideline values by more than six times (109 AQI points) [1], indicating a high level of pollution.

On the IQAir platform, air pollution indices for cities worldwide can be tracked both in real-time and retrospectively.

For all cities in Ukraine, including Kyiv, there is growing concern over the steadily increasing number of attacks from the aggressor state [4]. The use of high-tech weaponry of various types – including ballistic and cruise missiles, as well as unmanned aerial vehicles – leads not only to enormous economic damage but also to significant environmental pollution, including atmospheric pollution [5].

According to the Ministry of Environmental Protection and Natural Resources of Ukraine, the volume of pollutant emissions into the atmosphere during the ongoing military operations on Ukrainian territory is already comparable to the annual emissions of a metallurgical plant.

Figure 1 – Dynamics of Air Quality in the City of Kyiv for 2017–2024 According to the IQAir System

All these industrial, transportation, and military factors necessitate a more serious and comprehensive approach to developing an air quality monitoring system.

Review of Previous Research

The primary objective of creating an air quality monitoring system is to ensure continuous control over the concentrations of harmful chemical substances in the air, allowing for an objective assessment of the environmental condition (atmospheric air) and the timely identification of hazardous ecological situations.

Additionally, the goal is to provide local authorities with timely and reliable environmental data to support informed decision-making aimed at preventing (or reducing) negative factors that impact both the environment and human well-being.

Continuous observations are conducted under long-term programs, with an optimized number and spatial distribution of monitoring stations. These observations facilitate the evaluation, analysis, and forecasting of environmental conditions, thereby supporting informed decision-making processes at all levels of governance.

Due to the global deterioration of atmospheric air quality, expanding the monitoring network is a constant area of focus in scientific and environmental communities [6]. This includes defining key criteria for the placement of prospective monitoring sites [7] and exploring opportunities for more accurate environmental forecasting based on real-time statistical data [8].

The core tasks of establishing stationary posts and an automated air quality monitoring system include:

– Organizing systematic observations of atmospheric air conditions and identifying zones of ecological risk;
– Identifying sources and factors of negative anthropogenic impact on air quality and human health, and monitoring those sources;
– Creating and maintaining environmental information databases;
– Applying evaluation and forecasting tools to generate data that supports environmental decision-making;
– Developing well-grounded recommendations based on monitoring data for decisions related to ecological safety, environmental preservation, and sustainable natural resource use;
– Improving technical equipment and metrological support within the monitoring network.
– The development and improvement of the components of the existing automated air quality monitoring system's infrastructure, along with providing scientific support for its operation.

The main directions for the use of information obtained through the automated air quality monitoring system include:

– Providing authorities with up-to-date information about the state of atmospheric air for decision-making, monitoring compliance with environmental legislation, ensuring ecological safety, preserving the natural environment, and promoting sustainable natural resource use;
– Guaranteeing the public's right to access information about the state of the environment in their region;
– Meeting the information needs of enterprises, institutions, and organizations for decision-making regarding environmental safety and sustainable resource use;
– Supplying relevant government agencies—responsible for fulfilling obligations under international agreements—with necessary environmental data;

– Forecasting possible changes in ecosystems, medical-biological, and social consequences of ecological conditions in combination with social factors, including risk assessment;
– Modeling pathways toward achieving an environmentally safe status and the respective management decisions for implementation, including the creation of multi-factor models for economically viable and environmentally safe regional development;
– Promoting ecological awareness by making environmental information accessible to the public and the international community;
– Preparing data for environmental status reporting projects.

The foundational principles for improving the existing and expanding the prospective monitoring network include:
– Unifying technical and software infrastructure;
– Integrating informational subsystems across different monitoring areas for comprehensive data assessment;
– Implementing advanced information and analytical technologies;
– Introducing standardized formats for data provision and storage;
– Ensuring open access to information systems to support expansion and the introduction of new monitoring directions.

An analysis of the current situation in Ukraine, taking into account associated risks, underscores the urgent need to establish robust mechanisms for regulating the environmental condition of atmospheric air. These mechanisms should ensure predictable air quality and compliance with environmental protection standards by European environmental law, aligning with Ukraine's path toward European integration.

This article aims to develop a model for a prospective air quality monitoring system in Kyiv by identifying the optimal locations for its deployment.

To achieve this objective, the following research tasks must be completed:
– Analyze the current challenges related to air quality in the city of Kyiv;
– Assess the current state of the existing air quality monitoring system in the capital;
– Identify the primary directions for developing an effective monitoring system in Kyiv, considering the rapid urban expansion**.**

For systematizing and assessing the level of atmospheric pollution, one of the recognized indicators is the Comprehensive Air Pollution Index (API) [9], which is generally expressed through the Partial Pollution Index (I).

The Partial Pollution Index is a dimensionless value used to determine the amount of a specific pollutant and is calculated using the following formula:

$$I = \left(\frac{C_a}{MPAC}\right)^k, \quad (1)$$

where C_a – average concentration of the *i*-th substance, mg/m³
MPAC – maximum permissible average daily concentration of the pollutant, mg/m³;
k – a constant that takes a value depending on the hazard class of the substance, used to standardize the harmfulness of the studied substance relative to the harmfulness of sulfur dioxide (hazard class 3) (Table 1).

Table 1 – Hazard Class Constant of the Substance

Hazard Class Constant	1	2	3	4
k	1.5	1.3	1.04	0.85

The comprehensive air pollution index for a range of substances is calculated using the following formula:

$$API = \sum_{i=1}^{m} I_i \quad (2)$$

where: i – the ordinal number of the substance;
m – the total number of substances;
I – the partial pollution index of an individual pollutant.

According to existing assessment methods based on the API, four levels of air pollution are distinguished (Table 2).

Table 2 – Air Pollution Levels According to the API

API<5.0	API=5.0–7.0	API=7.0–14.0	API>14.0
low	elevated	high	very high

Presentation of the Main Material

Taking into account the Laws of Ukraine "On the Legal Regime of Martial Law", "On the Protection of the Interests of Reporting Entities and Other Documents During Martial Law and Wartime", and Presidential Decree No. 642022 dated February 24, 2022, "On the Introduction of Martial Law in Ukraine", as well as the situation caused by the military aggression of the Russian Federation against Ukraine, statistical authorities and other state institutions—holders of public information—have suspended the publication of statistical data and other information that could harm the interests of reporting entities since February 2022. Therefore, some data require clarification.

Air pollution monitoring in the city of Kyiv is carried out by the Borys Sreznevskyi Central Geophysical Observatory at 16 air pollution monitoring stations (APMS), located across eight districts of the capital (Fig. 2) [10]. There are no monitoring stations in the Sviatoshynskyi and Darnytskyi districts.

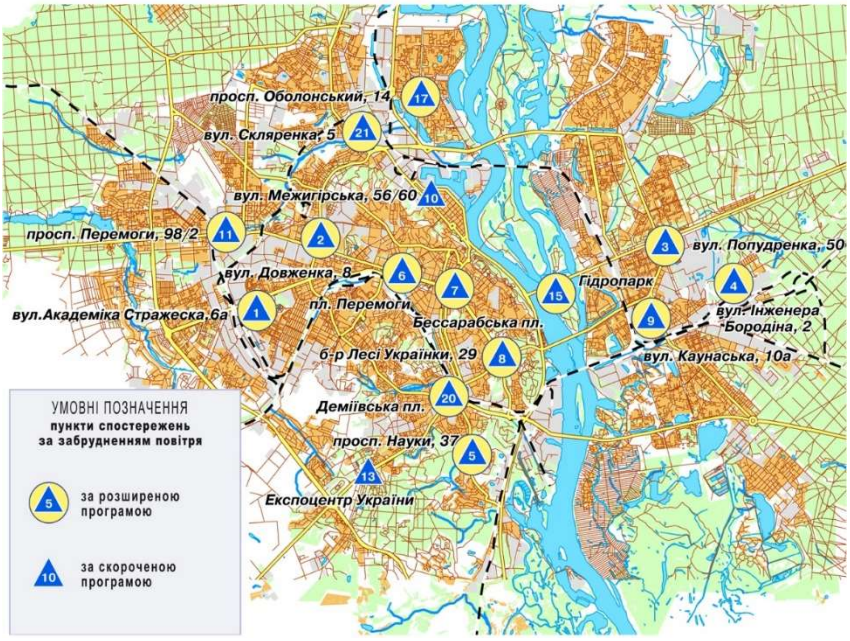


Figure 2 – Map of the Monitoring Network Observation Stations of the Borys Sreznevskyi Observatory in Kyiv

To assess air pollution, up to 6,250 samples are collected and analyzed on a monthly basis.

All stationary monitoring stations measure the concentration of major pollutants, including suspended particulate matter (dust), sulfur dioxide, carbon monoxide, and nitrogen dioxide. At one station, the concentrations of soluble sulfates and nitric oxide are also recorded.

Observations of specific substances – such as hydrogen sulfide, phenol, hydrogen fluoride, hydrogen chloride, ammonia, formaldehyde, and heavy metals (iron, cadmium, manganese, copper, nickel, lead,

chromium, zinc) –are conducted at selected stations. These are chosen based on the proximity of industrial enterprises and the city's busiest highways.

The monitoring network operates manually, which limits the observation program in terms of completeness and frequency. Air samples are analyzed four times per working day: at 1:00 a.m., 7:00 a.m., 1:00 p.m., and 7:00 p.m.

In 2023, a total of 81,663 samples were collected and analyzed. At monitoring stations №10 (Mezhyhirska St.) and №13 (Expocenter of Ukraine), only carbon monoxide levels were recorded throughout the year due to power outages. Fourteen stations continued monitoring the key pollutants mentioned above.

The overall air pollution level in Kyiv in 2023 was classified as high according to the Air Pollution Index (API) [11].

As a partial illustration, average daily concentrations of several air pollutants in Kyiv expressed as multiples of the maximum permissible average daily concentrations (MPAC) [11] during May 2023 are shown in Figure 3, and the air pollution levels at monitoring stations in Kyiv during the same period are shown in Figure 4.

The MPAC values for urban areas are approved by the Order of the Ministry of Health of Ukraine dated January 14, 2020, №52 [12].

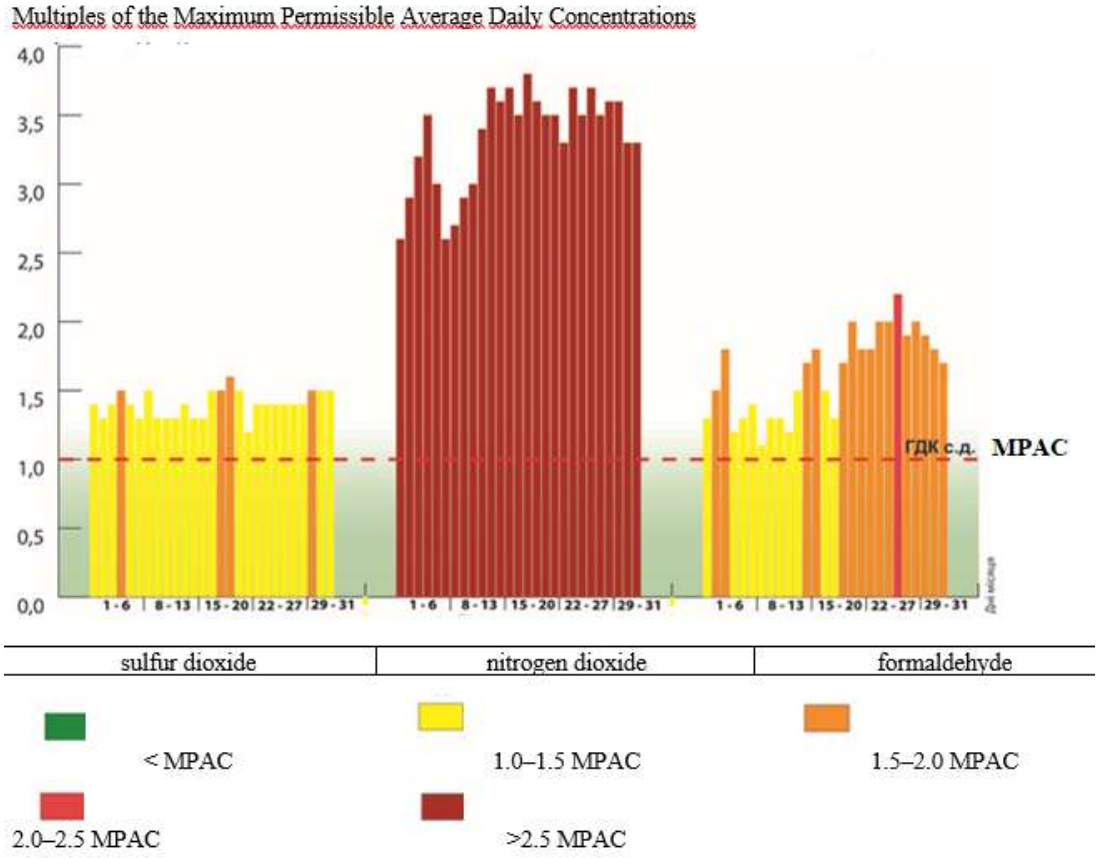
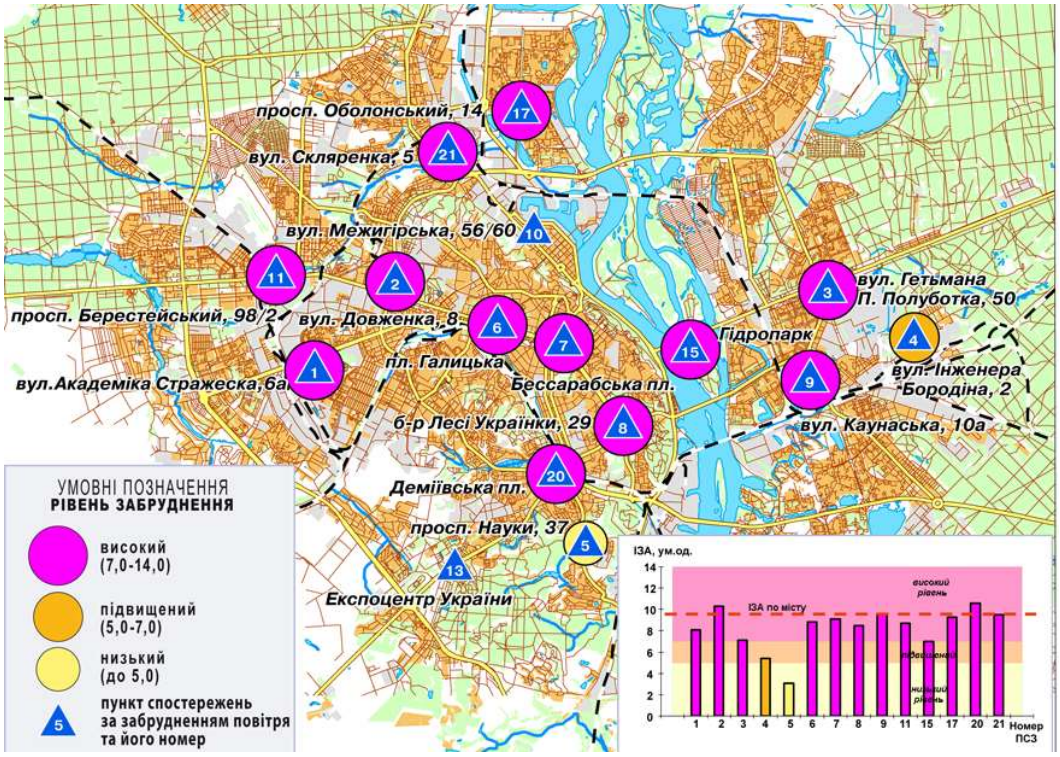


Figure 3 – Average Daily Concentrations of Air Pollutants in Kyiv as Multiples of the Maximum Permissible Average Daily Concentrations (May 2023)

Across Kyiv as a whole, exceedances of the maximum permissible average daily concentrations (MPAC) were observed for several pollutants: nitrogen dioxide by a factor of 2.3, formaldehyde by 1.4, sulfur dioxide by 1.5, phenol by 1.2, and nitric oxide by 1.0. These substances belong to hazard classes 2 and 3 and were the main contributors to air pollution in Kyiv throughout the year.

As an example, the results of monitoring pollutant concentrations during May 2023 at one of the city's observation stations are presented in Figure 5 [11].



High pollution level (7.0–14.0) *Increased pollution level (5.0–7.0)* *Low pollution level (<5.0)*

Figure 4 – Air Pollution Levels at Monitoring Stations in Kyiv in May 2023

Throughout the year, the average daily concentrations of suspended particulate matter ranged from 0.5 to 0.7 MPAC. The maximum concentrations recorded at the city's stations ranged between 0.2 and 0.4 of the maximum permissible one-time concentration ($MPC_{m.r.}$).

Sulfur dioxide levels exceeded the MPAC at all city stations except for Station №5 (Nauky Avenue, near the observatory's meteorological site), where the concentration was 0.1 MPAC. The highest average daily concentrations of sulfur dioxide were recorded at Demiivska Square (Station №20) – 1.9 MPAC, and at Bessarabska Square (Station №7), Halytska Square (Station №6), and Oleksandr Dovzhenko Street (Station №2) – 1.89 MPAC. Nine other stations recorded average daily concentrations ranging from 1.3 to 1.7 MPAC. The maximum concentrations of sulfur dioxide across the city ranged from 0.1 to 0.5 $MPC_{m.r.}$.

For carbon monoxide, the highest average daily concentrations were recorded on Beresteiskyi Avenue (Station №11) and S. Sklyarenka Street (Station №21) – 0.6 MPAC. At other stations, average daily concentrations ranged from 0.2 to 0.5 MPAC. Citywide, the average daily carbon monoxide concentration was 0.4 MPAC.

The highest maximum concentrations of this pollutant were observed in the Hydropark area (Station №15) – 4.0 $MPC_{m.r.}$, on Mezhyhirska Street (Station №10) – 2.4 $MPC_{m.r.}$, on Beresteiskyi Avenue (Station №11) and Akademika Strazheska Street (Station №1) – 1.7 $MPC_{m.r.}$, and on Halytska Square (Station №6), S. Sklyarenka Street (Station №21), and Inzhenera Borodina Street (Station №4) – ranging from 1.3 to 1.5 $MPC_{m.r.}$.

The frequency of carbon monoxide exceedances of the maximum one-time permissible concentration ($MPC_{m.r.}$) relative to the total number of observations across the city was 0.3 %. For comparison, this figure was 0.9 % in 2022. The highest number of $MPC_{m.r.}$ exceedance cases were recorded at Station №21 (S. Sklyarenka St.) and Station №11 (Beresteiskyi Ave.) – 1.3 % and 1.0 %, respectively.

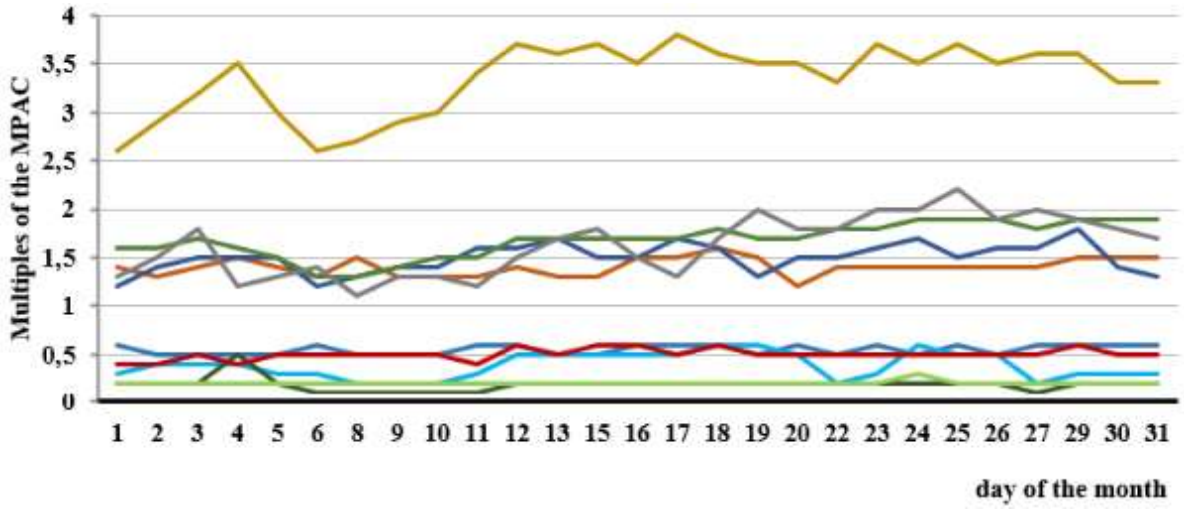


Figure 5 – Average Concentrations of Air Pollutants in Kyiv as Multiples of the Maximum Permissible Average Daily Concentrations (May 2023)

The content of nitrogen dioxide, based on average daily and maximum concentrations, exceeded the corresponding maximum permissible concentrations (MPC) at almost all stations. The highest average daily concentrations of nitrogen dioxide were observed at stations located near highways with heavy traffic: at Halytska Square (Station №6), Bessarabska Square (Station №7), Beresteiskyi Avenue (Station №11), Kaunaska Street (Station №9), and S. Sklyarenka Street (Station №21) – 2.8 MPAC, at Demiivska Square (Station №20) – 2.7 MPAC, at Hetman Polubotko Street (Station №3) – 2.6 MPAC. At other stations, average daily concentrations ranged from 2.0 to 2.5 MPAC, and at Nauky Avenue (Station №5) (near the observatory's meteorological site – the city's green zone), 0.9 MPAC.

Maximum one-time concentrations of nitrogen dioxide were recorded at: S. Sklyarenka Street (Station №21) and Kaunaska Street (Station №9) – 1.6 $MPC_{m.r}$.., at Halytska Square (Station №6) and Inzhenera Borodina Street (Station №4) – 1.5 $MPC_{m.r}$. At other stations, maximum nitrogen dioxide concentrations ranged from 1.1 to 1.3 $MPC_{m.r}$. The frequency of exceedances of the maximum one-time MPC out of the total number of observations across the city was 2.4 %. For comparison, in 2022, this figure was 7.5 %. The highest frequencies were recorded at Station №6 (Halytska Sq.) – 8.3 %, Station №9 (Kaunaska St.) – 7.7 %, Station №7 (Bessarabska Sq.) – 7.6 %, and Station №21 (S. Sklyarenka St.) – 6.7 %.

The average daily content of nitric oxide (measured only at Station №20 (Demiivska Sq.)) was 1.0 MPAC, the maximum – 0.4 $MPC_{m.r}$.

Phenol content, measured at seven stations, exceeded the corresponding MPAC at all stations with average daily concentrations ranging from 1.1 to 1.4 MPAC. The highest average daily concentration of phenol was observed at Oleksandr Dovzhenko Street – 1.4 MPAC. Maximum one-time phenol concentrations in the air ranged from 0.8 to 0.9 $MPC_{m.r}$.

Formaldehyde content in the air was measured at 13 stations. The average daily concentrations of this pollutant exceeded the daily MPAC at 12 of the stations where it was measured, ranging from 1.3 to 1.7 MPAC. At Station №5 (Nauky Ave.), the average daily concentration was 0.8 MPAC. The highest average daily formaldehyde concentrations were observed on Beresteiskyi Avenue (Station №11) and at Bessarabska Square (Station №7) – 1.7 MPAC. Maximum formaldehyde concentrations at all stations ranged from 0.2 to 0.9 $MPC_{m.r}$.

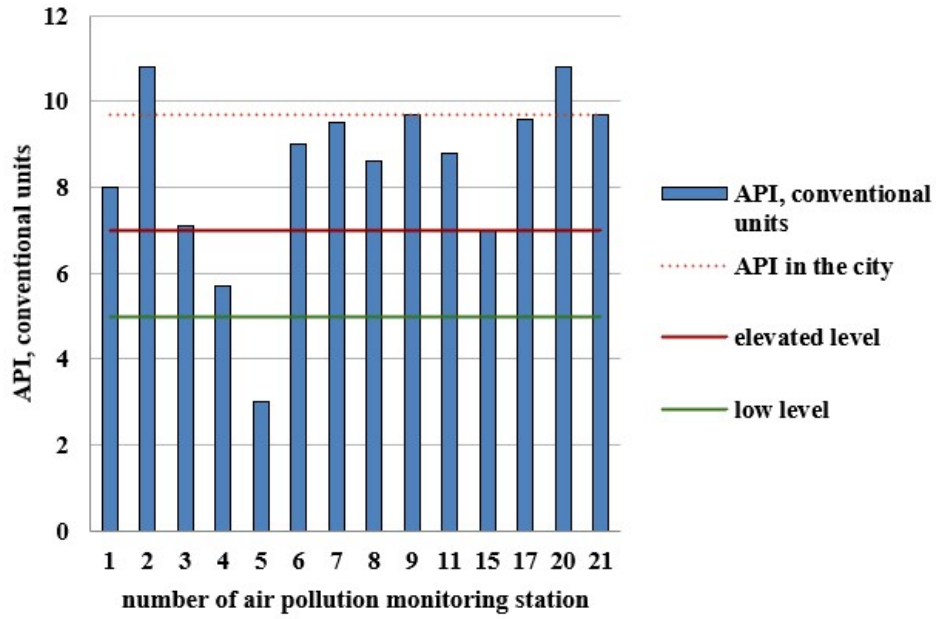
Average daily concentrations of hydrogen sulfide at the three stations where this pollutant was measured were 0.002 mg/m³, and maximum concentrations ranged from 0.0037 to 0.0053 mg/m³ (0.5–0.7 $MPC_{m.r}$.).

The average daily and maximum concentrations of other specific pollutants did not exceed the relevant sanitary-hygienic standards and were as follows: hydrogen fluoride – 0.1–0.2 MPAC and 0.1 $MPC_{m.r}$.., ammonia – 0.2 MPAC and 0.1–0.3 $MPC_{m.r}$. respectively. For hydrogen chloride, the average daily concentrations at stations were at the level of 0.3 MPAC, and the maximum one-time concentrations ranged from 0.8 to 1.0 $MPC_{m.r}$.

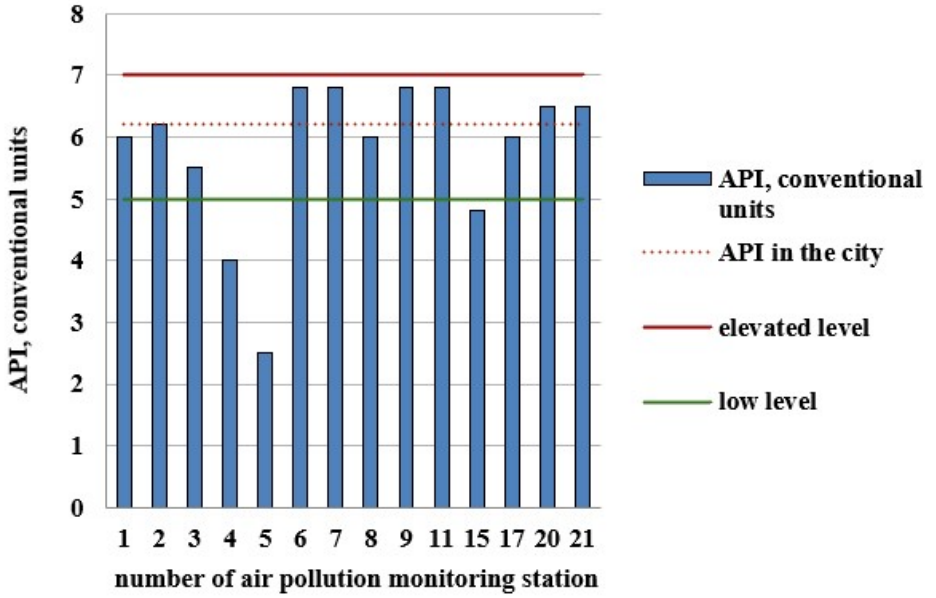
The content of heavy metals in the air in 2023 was significantly below the maximum permissible levels. The average daily concentrations of lead, manganese, chromium, iron, cadmium, copper, nickel, and zinc at all stations and across the city were at levels of 0.0–0.1 MPAC. The maximum average monthly concentrations of heavy metals in the city's air were: lead and cadmium – 0.2 MPAC in January at Station №21 (S. Sklyarenka St.), manganese, iron, and nickel – 0.1 MPAC.

During 2023, increases in the average monthly concentrations of pollutants were mainly observed during the warmer months [11]. Thus, formaldehyde levels increased from May to September, while nitric oxide levels were highest in May, and phenol levels increased from May to September. Nitrogen dioxide content throughout the year averaged approximately 2.3 MPAC, with higher values (2.6–3.3 MPAC) in May–August. Starting from October, a decrease in the pollutant concentration was observed, reaching 1.5–1.7 MPAC. The sulfur dioxide content throughout the year was approximately 1.4 MPAC. During the cold period of the year (January–March and November–December), the average monthly concentrations of sulfur dioxide rose to 1.6–1.8 MPAC, coinciding with the heating season in the city. Concentrations of suspended particles (dust), hydrogen fluoride, ammonia, and heavy metals fluctuated slightly during the year.

According to the Air Pollution Index (API), the air pollution level in the city was classified as high throughout the year [11]. The most polluted air in Kyiv was observed in June (Fig. 6a). Only in October and December the pollution level decreased slightly and was classified as elevated (Fig. 6b-6d).



a



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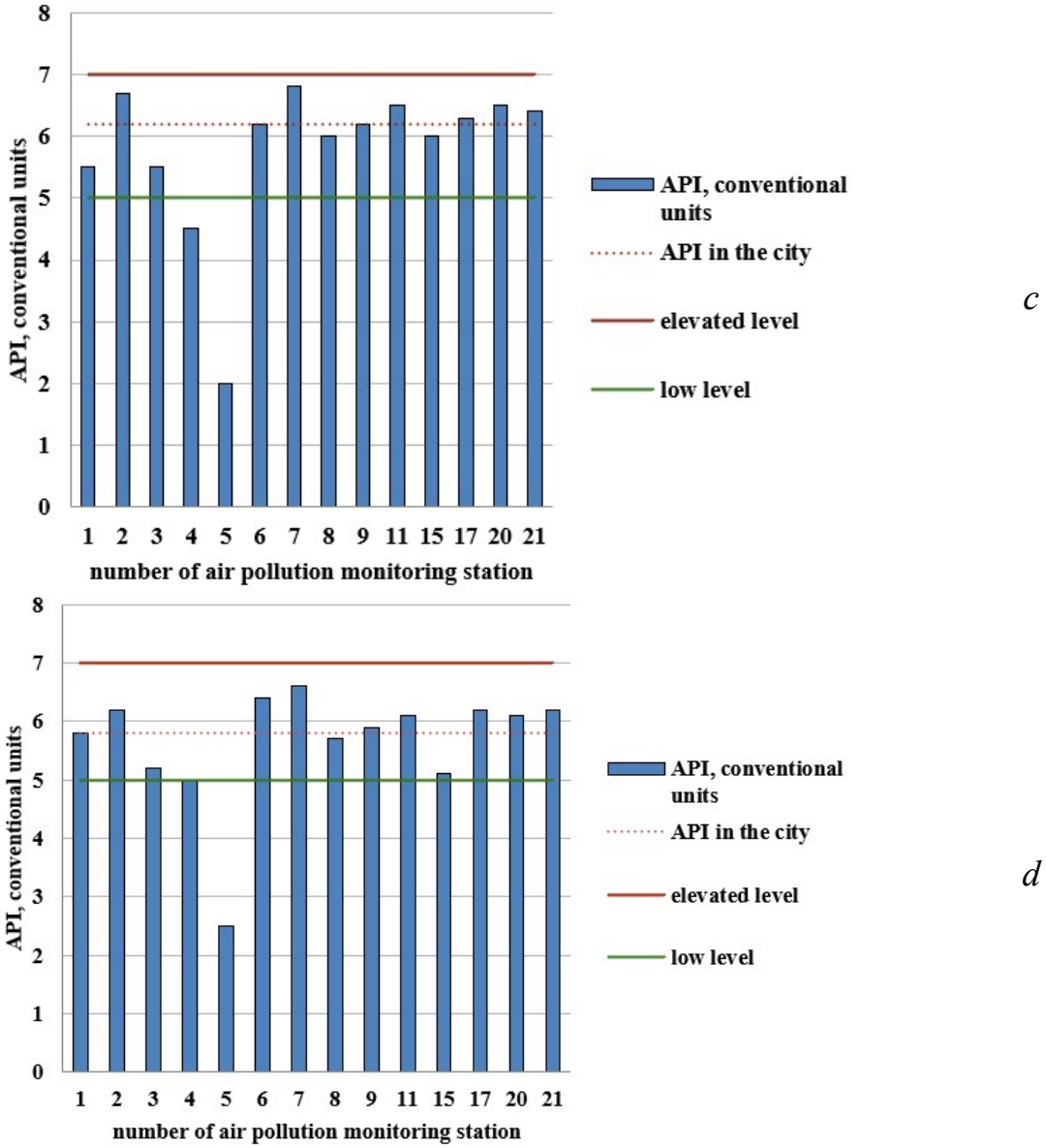


a - June 2023; b - October 2023; c - November; d - December 2023

Figure 6 – The Dynamics of Air Pollution Index (API) at monitoring stations in Kyiv during 2023

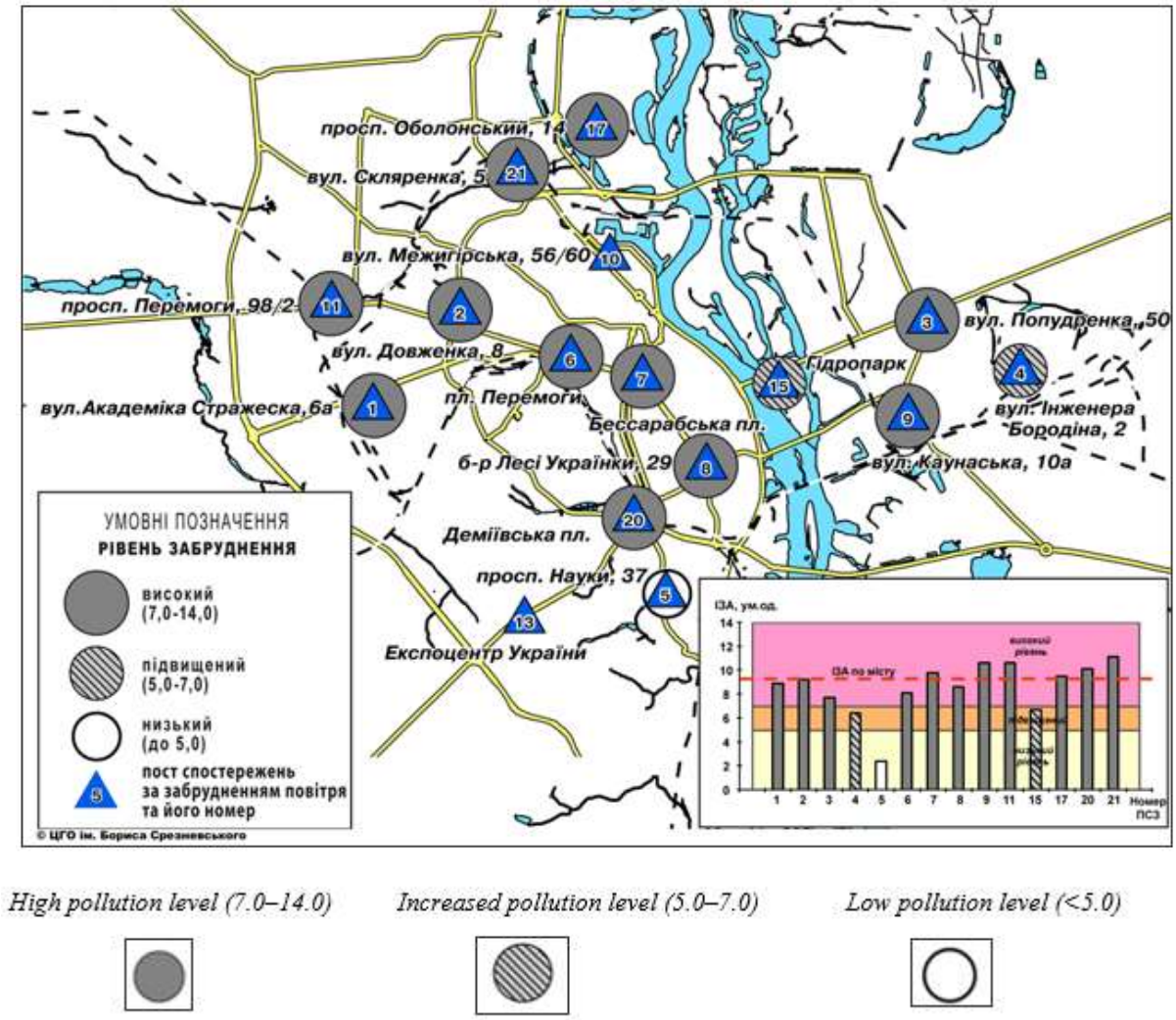
Throughout 2023, based on average annual concentrations of pollutants, the air pollution level at 9 monitoring stations in the city was assessed as high [11].

The highest levels of pollution were recorded at Kaunaska Street (Station №9), Beresteiskyi Avenue (Station №11), and S. Sklyarenka Street (Station №21).

Also classified within the high pollution zone were the areas of Demiivska Square (Station №20), Bessarabska Square (Station №7), Akademika Strazheska Street (Station №1), Oleksandr Dovzhenko Street (Station №2), Halytska Square (Station №6), Lesi Ukrainky Boulevard (Station №8), Obolonskyi Avenue (Station №17), and Popudrenka Street (Station №3).

An elevated pollution level was recorded in the Hydropark area (Station №15) and on Inzhenera Borodina Street (Station №4).

The lowest pollution level (low) was observed in the area of Nauky Avenue (Station №5) (Figure 7).



High pollution level (7.0–14.0) *Increased pollution level (5.0–7.0)* *Low pollution level (<5.0)*

Figure 7 – Zones with the Highest and Lowest Air Pollution Levels (According to the API) in Kyiv in 2023

Compared to the previous year, the air pollution level in the city, according to the API, remained unchanged. (API_2022 = 7.6 conventional units; API_2023 = 7.7 conventional units), Yet it continued to be classified as high.

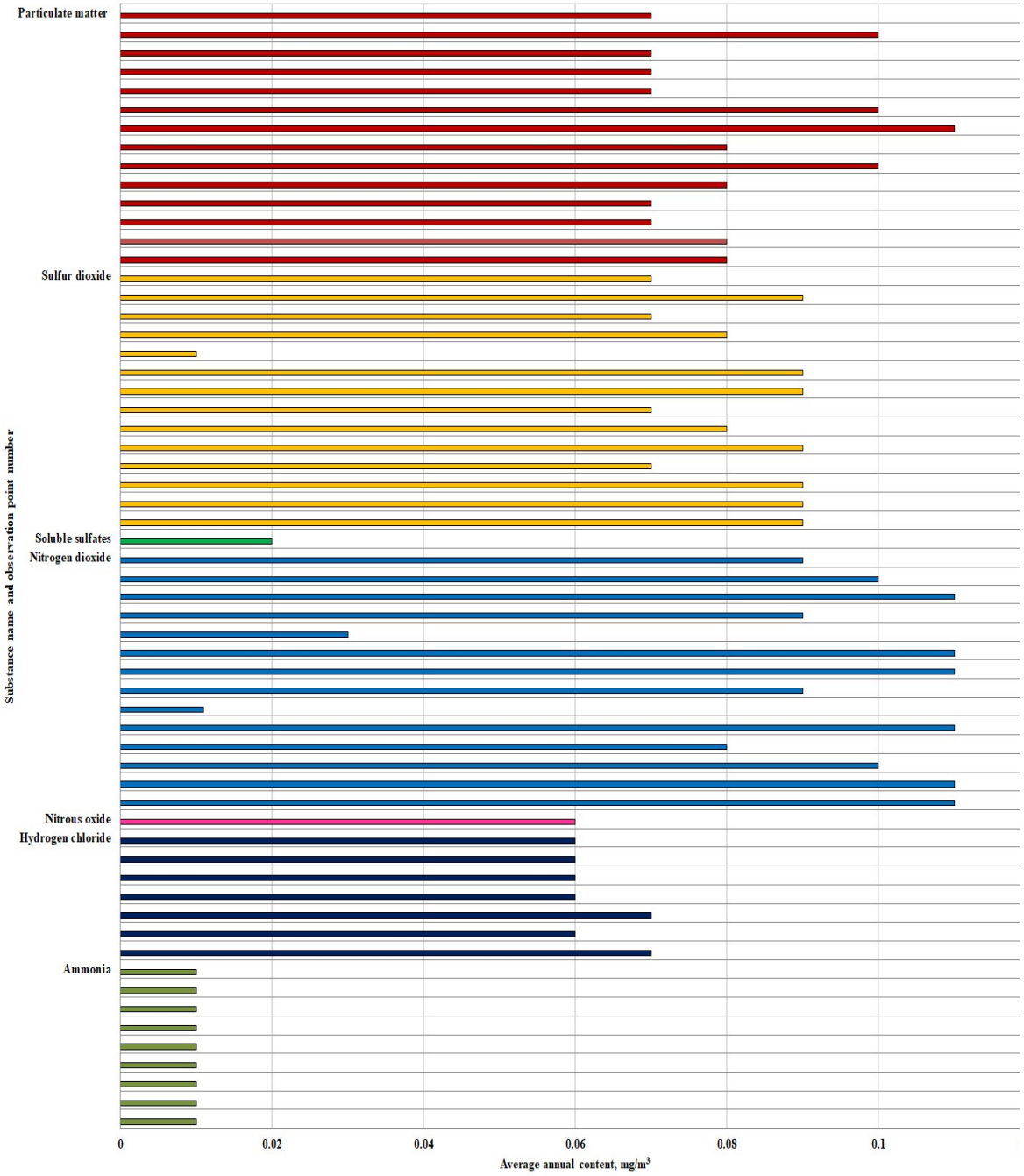
The high level of air pollution is attributed to the average annual concentrations of dominant pollutants, including nitrogen dioxide, formaldehyde, sulfur dioxide, phenol, and nitric oxide.

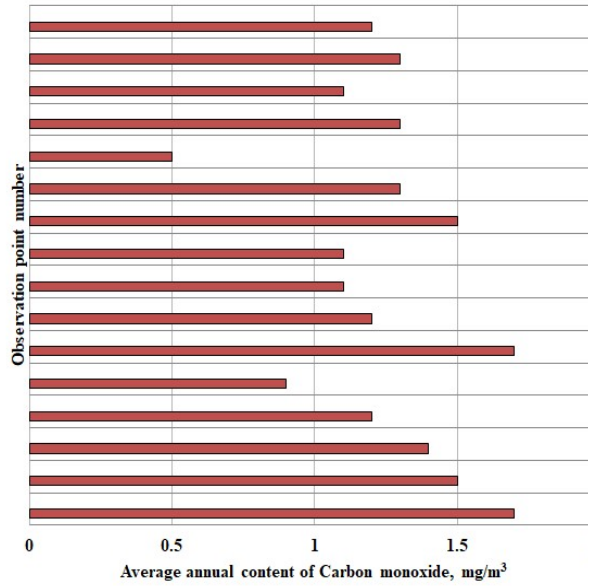
In particular, in the capital, the average annual concentrations of sulfur dioxide, nitrogen dioxide, formaldehyde, and phenol exceeded the maximum permissible average daily concentrations by 1.5 to 2.5 times (Figure 8).

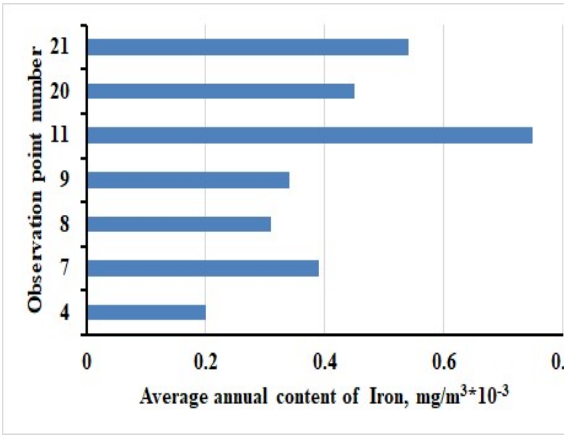
The maximum permissible concentrations for these pollutants are provided in Figure 5.

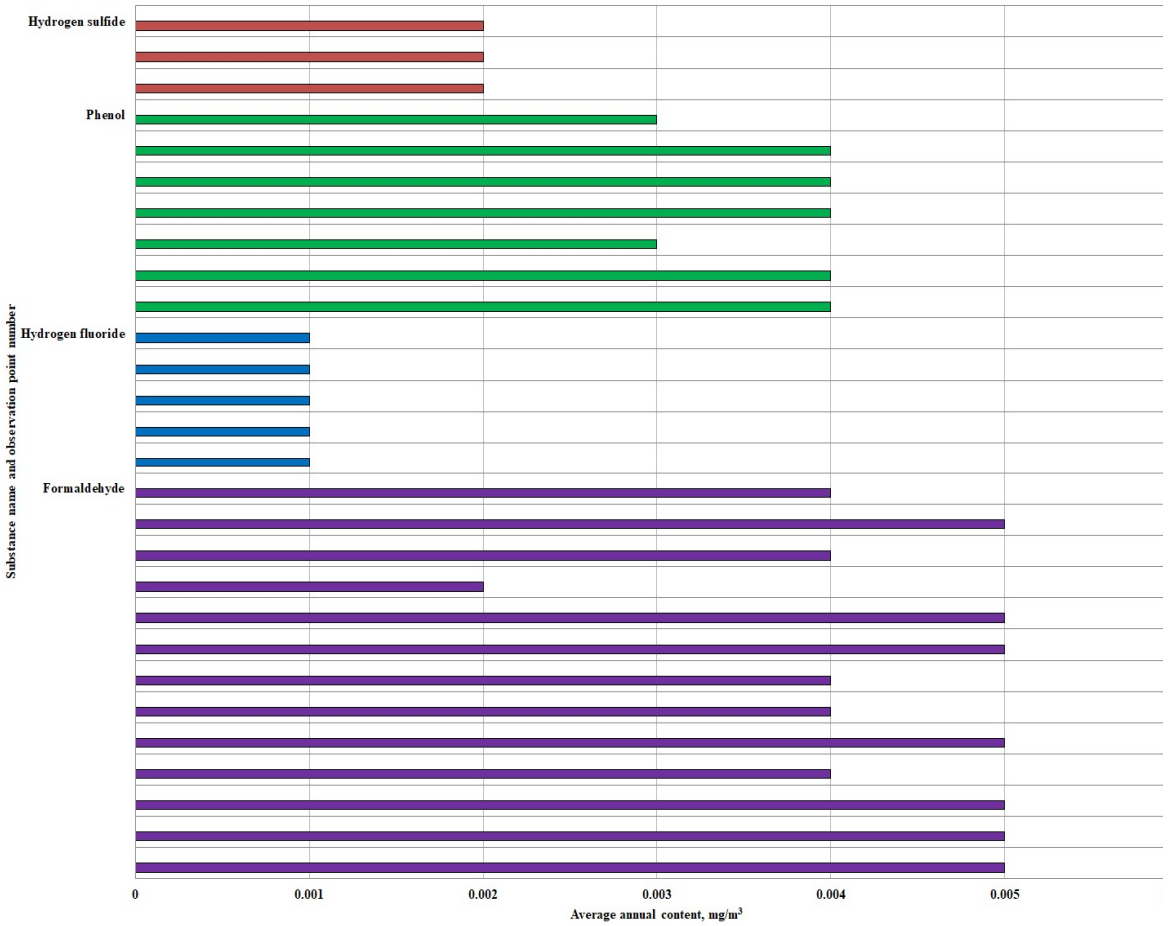
It should be noted that since 2022, there has been a slight decrease in the average annual concentrations of nitrogen dioxide, nitric oxide, and formaldehyde. However, the concentration of sulfur dioxide in the air has increased significantly, and the level of phenol has partially risen. The content of other pollutants has remained practically unchanged [11].

In the current air quality monitoring system in Kyiv, data collection and processing are minimally automated, based on laboratory-chemical methods of sample analysis, and are used more for statistical analysis than for real-time decision-making [10].


Particulate matter
Sulfur dioxide
Soluble sulfates
Nitrogen dioxide
Nitrous oxide
Hydrogen chloride
Ammonia
Substance name and observation point number
0
0.02
0.04
0.06
0.08
0.1
Average annual content, mg/m3


Observation point number
0
0.5
1
1.5
Average annual content of Carbon monoxide, mg/m3


Observation point number
21
20
11
9
8
7
4
0
0.2
0.4
0.6
Average annual content of Iron, mg/m3*10-3


Substance name and observation point number
Hydrogen sulfide
Phenol
Hydrogen fluoride
Formaldehyde
0
0.001
0.002
0.003
0.004
0.005
Average annual content, mg/m3

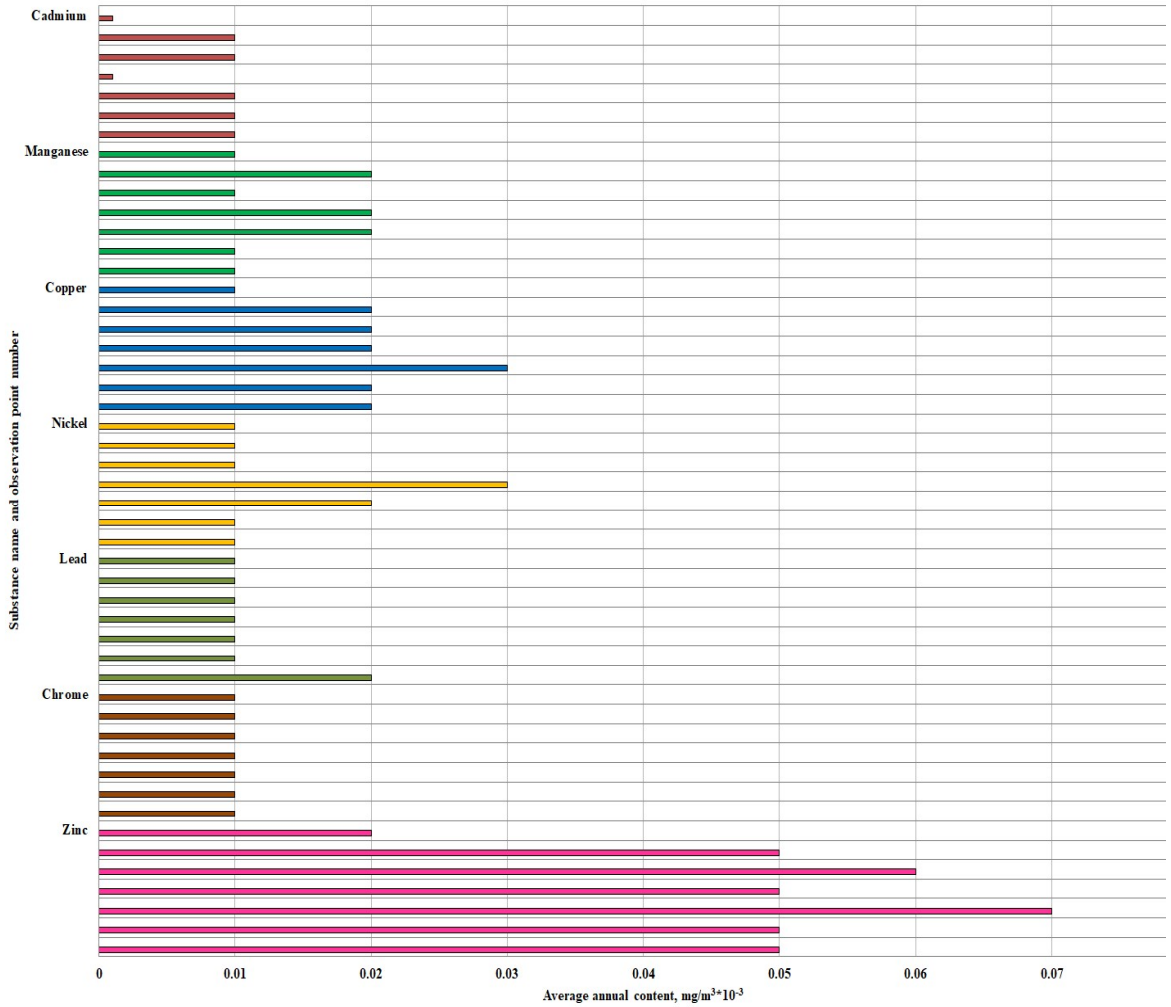


Figure 8 – Average Annual Concentration of Pollutants in the Atmospheric Air of Kyiv in 2023 by Monitoring Station (APMS)

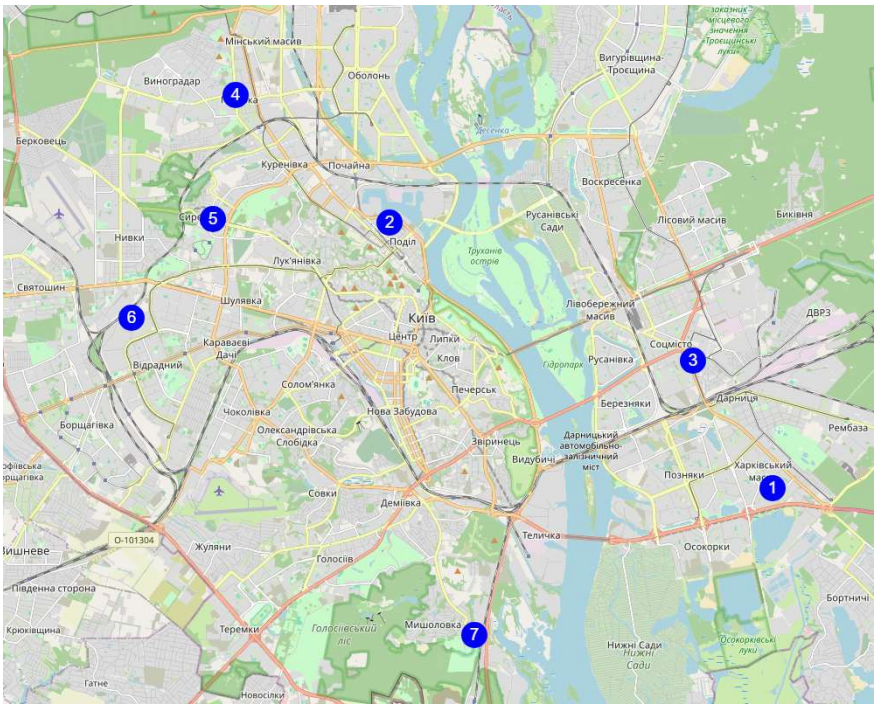
The main shortcomings that reduce the effectiveness of the functioning air monitoring system in Kyiv include:

– the absence of a unified observation network;
– outdated technical and methodological support for monitoring;
– lack of modern technical equipment in the monitoring centers;
– lack of coordination between elements of the information technologies used;
– inconsistency of regulatory and legal frameworks with modern monitoring requirements.

As a result, the responsible authorities are practically unable to effectively manage air quality at various levels to prevent negative environmental changes and ensure compliance with environmental safety standards, which leads to adverse consequences for both the environment and public health.

The entity responsible for air quality monitoring in the city of Kyiv is the executive body of the Kyiv City Council (Kyiv City State Administration – KCSA) – the Department of Environmental Protection and Climate Change Adaptation [13].

In Kyiv, seven reference (high-precision) air quality monitoring stations have been installed, located in the Darnytskyi, Dniprovskyi, Podilskyi, Shevchenkivskyi, Sviatoshynskyi, and Holosiivskyi districts (Figure 9).



1 – 26 Arkhitektora Verbytskoho St.;2 – 28 Turivska St.;
3 – 71 Kharkivske Highway; 4 – 64G European Union Avenue;
5 – 20 Shchuseva St.; 6 – 97 Beresteiskyi Avenue; 7 – 22 Kytaivska St.

Figure 9 – Map of the Locations of Reference Air Quality Monitoring Stations of the Kyiv City State Administration (KCSA)

In addition to the reference stations, the capital also has 46 indicative sensors installed, which help monitor air quality in areas of Kyiv where main stations are absent.

The information collected and processed by air quality monioring entities is considered official. Data from the monitoring system is displayed on the website of the respective Department, in the Kyiv Digital mobile application, and on the SaveEcoBot platform [14].

The consolidated results of air pollution monitoring observations for 2023, as determined by the KCSA air quality monitoring system, are presented in Figure 10.

The ratio of pollutant concentrations at different monitoring stations varied within a narrow range. It should be noted that for almost every component, pollutant concentration values exceeding even their maximum one-time permissible concentrations were periodically recorded at all monitoring stations throughout the year. At Monitoring Station №1, monitoring was also carried out for the following substances (average annual concentration, μg/m³): hydrogen sulfide – 6.4 μg/m³, ammonia – 1.9 μg/m³, methyl mercaptan – 6.2 μg/m³, ethyl mercaptan – 3.5 μg/m³. At Monitoring Stations №6 and №7, benzene content in the air was also determined. The average annual concentrations of benzene in the air were 0.3 μg/m³ and 0.2 μg/m³, respectively. No exceedances of the maximum permissible average daily concentrations of these substances in the air were recorded during the year.

In 2024, the Kyiv City Development Strategy until 2027 was approved [15]. It outlines the directions and trends for the development of the city of Kyiv, or more precisely, the Kyiv agglomeration, in the coming years.

With the full-scale invasion of the Russian Federation into the territory of Ukraine, an urgent need arose to revise the existing regulatory and administrative acts in the field of urban planning and, in particular, to amend the General Plan of Kyiv taking into account recent trends. By decision of the Kyiv City Council dated 11.04.2024 №3778343 "On urgent measures to ensure the sustainable development of the city of Kyiv" a comprehensive approach was defined for the development of urban planning documentation projects designed to justify the long-term strategy for planning and developing the territory of the city of Kyiv.

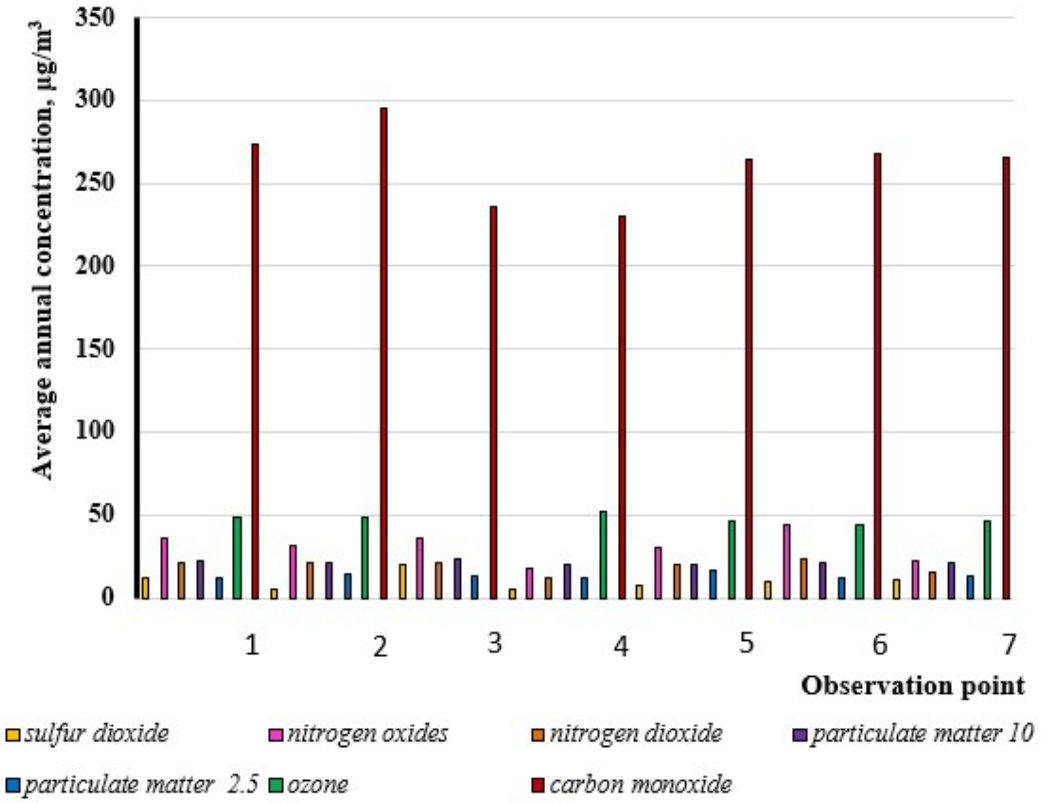


Figure 10 – Results of Air Pollution Monitoring Observations in 2023 (According to Data from the KCSA Air Quality Monitoring System)

At the same time, taking into account the requirements for publishing datasets in the form of open data during martial law, the publication of general plans of settlements, zoning plans, detailed territory plans, urban planning documentation of territorial communities, and their projects is not being carried out. Due to these restrictions, problems have arisen in the development of urban planning documentation and the conduct of public consultations (hearings) on urban planning documentation at the local level, in accordance with Ukrainian legislation. The result of such restrictions caused by the war has been a low rate of approved detailed territory plans.

Discussions about the creation of the Kyiv agglomeration have been ongoing for at least five years; however, it currently exists only de facto, not de jure. An agglomeration is understood as a cluster of settlements (mainly cities) that are united into a single whole by economic, labor, social, and cultural ties.

The most well-known agglomerations in the world are Tokyo, New York, London, and Paris.

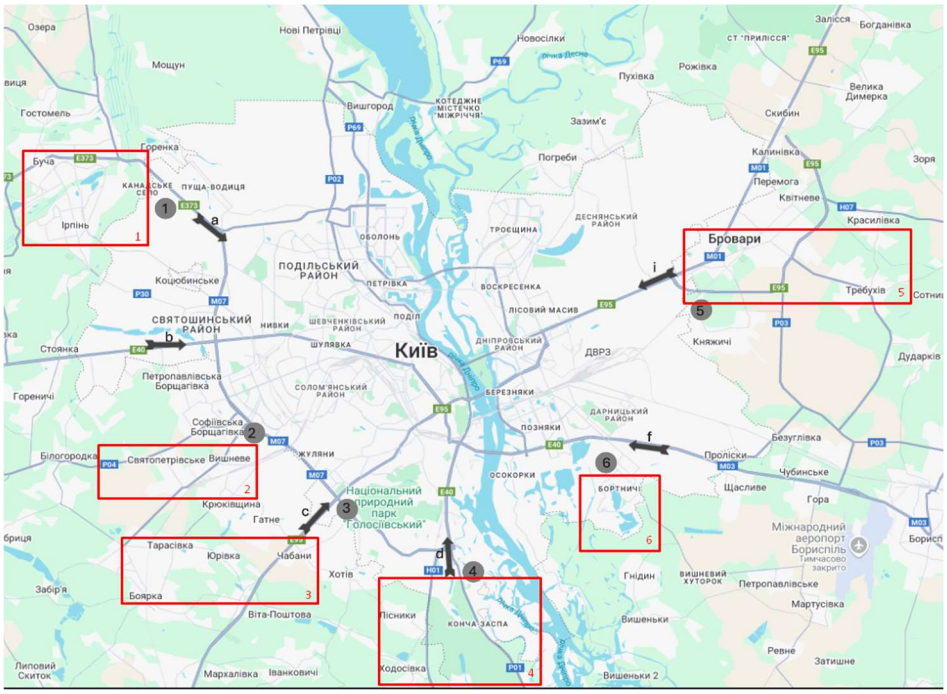
Ukraine also has agglomerations. In fact, they have formed around all regional centers and some large cities of regional significance (Kryvyi Rih, Kremenchuk). Such clusters of settlements, which have a single core center and subordinate peripheries, are referred to as monocentric (e.g., Kyiv, Kharkiv, Lviv, Dnipro, Odesa). Less frequently, polycentric agglomerations (conurbations) are found, which include several equally significant core cities (e.g., Sievierdonetsk–Lysychansk, Uzhhorod–Mukachevo).

The Kyiv agglomeration is the largest in Ukraine. It includes the capital and its suburbs – Brovary, Boryspil, Vasylkiv, Vyshhorod, Vyshneve, Boyarka, Obukhiv, Irpin, and Bucha. Fastiv and Bila Tserkva, located more than 60 kilometers from Kyiv and not sharing a direct border with it, are also considered part of the capital's agglomeration.

Approximately 25 % of residents of settlements within 30 kilometers of Kyiv and 17 % of residents of more distant cities travel to the capital daily. Most of them reach the town by scheduled public transport (63 % and 58 %, respectively), private car (32 % and 22 %), or commuter train (15 % and 3 %).

The lack of convenient transportation often forces suburban residents to rely on personal cars. These vehicles enter Kyiv, exacerbating the traffic congestion situation and leading to a significant deterioration of air quality in Kyiv and its suburbs.

The structure of the Kyiv agglomeration can be divided into three zones: the core, the first ring, and the second ring of satellite cities. Some cities have grown so extensively that they have formed their agglomerations. These include the following agglomerations (Figure 11):



- agglomeration zones: Bucha (1), Vyshneve (2), Boyarka (3), Obukhiv–Ukrainka (4), Brovary (5), Zolochiv (6);

– main road transport arteries (a – i);

- approximate locations for the installation of monitoring stations.

Figure 11 – Map of the Approximate Placement of Air Quality Monitoring System Locations in Kyiv

- Brovary: Brovary–Kalynivka–Velyka Dymerka – 140 thousand people (as of 01.10.2014);
- Bucha: Bucha–Irpin–Hostomel–Vorzel–Nemishaieve–Borodianka – 180 thousand people;
- Obukhiv–Ukrainka: Obukhiv–Ukrainka–Trypillia – 50 thousand people;
- Vyshneve: Vyshneve–Sviatopetrivske – 40 thousand people;
- Boyarka: Boyarka–Tarasivka–Nove – 40 thousand people;
- Zolochiv: Hnidyn–Vyshenky–Petrovske – 5.9 thousand people (formed since 2020);
- urban development from Petropavlivska Borshchahivka to Lisnyky.

Given the continuous increase in vehicle-related environmental pressure on the city, and in order to make informed decisions regarding the future improvement of air quality in Kyiv, the issue of expanding the network of pollution monitoring stations within the Kyiv agglomeration remains highly relevant.

The determination of locations for the placement of air quality monitoring systems is based on a set of technical, environmental, social, and regulatory criteria.

The regulatory criteria include:

- legislative requirements: compliance with Directive 200850EC (for EU countries), the Law of Ukraine "On the Protection of Atmospheric Air," and other regulatory documents;

- zoning classification: division of territories by type – ackground, urban, industrial, transport, residential, recreational, etc.

Among the geographic and demographic criteria are:

- population density, with priority given to densely populated areas;
- natural and climatic conditions, such as terrain, wind direction, and the presence of atmospheric inversions;
- location relative to pollution sources, including industrial facilities, transport arteries, boiler stations, etc.

Environmental criteria include:

- presence or risk of exceeding maximum permissible concentrations;
- presence of vulnerable sites: schools, hospitals, kindergartens, etc.;
- presence of natural sites: national parks, water bodies, reserves.

Technical criteria include:

- infrastructure availability, i.e. access to electricity and internet;
- safety of the installation site;
- absence of measurement interference, such as zones with high dust deposition, magnetic fields, or external noise sources.

Social and strategic criteria include:

- community requests, primarily taking into account complaints and appeals from local residents;
- support from local authorities;
- ensuring representative territorial coverage, reflected in the even distribution across districts..

Economic feasibility is determined by:

- cost of installing and maintaining measurement equipment;
- monitoring efficiency in terms of cost-effectiveness (cost-to-informational-value ratio).

Based on the above criteria for expanding the air monitoring network, site selection is proposed with the following perspectives:

- in all key districts bordering the Kyiv agglomeration zones, ensuring even coverage while considering microclimate characteristics;
- near major transport arteries and directions most affected by air strikes from the Russian Federation, which potentially pose fire risks and corresponding emissions of air pollutants;
- in densely populated districts, especially those inhabited by vulnerable groups;
- with consideration for prevailing winds, air inversions, and the microclimates of various districts;
- at strategic points where peak pollution events are possible;
- in locations with access to electricity, internet, and protected areas.

Approximate locations for the installation of monitoring stations are shown in Figure 11.

Conclusions

1. The results of monitoring observations conducted by the Borys Sreznevskyi Central Geophysical Observatory and the assessment of Kyiv's air quality in 2023 indicate that the overall air pollution level in the city for that year was rated as high according to the Air Pollution Index (API). Specifically, the annual average concentrations of sulfur dioxide, nitrogen dioxide, formaldehyde, and phenol exceeded the daily maximum permissible concentrations by 1.5 to 2.5 times the recommended levels.
2. The "weak points" of the existing air quality monitoring system in Kyiv have been identified. These include insufficient territorial coverage of the metropolis by monitoring stations and the lack of modern technical and informational infrastructure. The main criteria for selecting new locations for expanding the city's monitoring system have been outlined.
3. Tentative locations for the placement of air quality monitoring stations in Kyiv have been proposed, taking into account the distribution of major development hubs within the Kyiv agglomeration.

Prospects for Further Research

The authors plan to conduct future studies focused on environmental risk assessment related to industrial pollution in the region. This includes ranking districts of the Kyiv region by type and degree of risk, with the goal of developing priority measures to minimize and prevent pollution within the Kyiv agglomeration.

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ВИЗНАЧЕННЯ ЛОКАЦІЙ ДЛЯ РОЗБУДОВИ СИСТЕМИ МОНІТОРИНГУ ЯКОСТІ АТМОСФЕРНОГО ПОВІТРЯ УРБАНІСТИЧНОЇ ТЕРИТОРІЇ, ЩО ІНТЕНСИВНО РОЗВИВАЄТЬСЯ (НА ПРИКЛАДІ МОДЕЛІ МІСТА КИЄВА)

Сучасний розвиток суспільства характеризується великою чисельністю населення, а отже, і зростанням економічних та енергетичних потреб. Потужні викиди промислових шкідливих речовин в атмосферу, вихлопні гази від автотранспорту, застосування хімічних речовин у побуті спричиняють погіршення стану атмосферного повітря та зміну клімату в цілому. Крім того, Україна зіштовхнулась з безпрецедентною шкодою для якості атмосферного повітря, що спричинене широкомасштабною збройною агресією. Київ займає одне з перших місць по забрудненню повітря в країні і час від часу фігурує в топі самих забруднених міст світу. Так, у 2023 році в місті Києві середньорічні концентрації діоксиду сірки, діоксиду азоту, формальдегіду та фенолу перевищували середньодобові граничнодопустимі концентрації у 1,5–2,5 рази. Найгірша ситуація в плані якості атмосферного

повітря міста склалася в районі Деміївської площі.
Центральна геофізична обсерваторія, яка здійснює моніторинг атмосферного повітря міста і має найбільш детальну інформацію про якість повітря, потребує нагального вдосконалення через розширення мережі системи спостереження і підвищення рівня технічного та інформаційного забезпечення.
Одночасно столиця є лідером по діжіталізації міста не тільки в Україні, а й в Європі. На тлі існуючої ситуації оновлення та розширення системи моніторингу стану довкілля Києва, зокрема якості атмосферного повітря, має бути пріоритетним.
В той же час постійно активізується зв'язок між столицею та областю, що супроводжується підвищенням антропогенного навантаження на повітря від транспортних засобів. В роботі представлено структуру Київської агломерації та запропоновано проєкт орієнтовного розміщення локацій системи моніторингу якості атмосферного повітря міста Києва з урахуванням розташування основних осередків забудови Київської агломерації.

***Ключові слова**: система моніторингу навколишнього середовища, викиди забруднюючих речовин, якість повітря, урбанізована територія*

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