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Formation of a regional system for environmental monitoring of atmospheric air in tourist destinations

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Abstract. Despite the development of environmental monitoring systems in Ukraine, existing approaches do not take into account the specifics of tourist regions, which creates significant challenges for assessing environmental risks and ensuring air quality in conditions of intense tourist flows. The aim of the study was to substantiate the concept of forming a regional system for monitoring and managing the environmental safety of tourism in the territorial communities of the Ivano-Frankivsk region, taking into account European standards for atmospheric air quality control. The methodological basis was the analysis of European and national environmental legislation, geospatial modelling based on OpenStreetMap open data, indicators of tourist capacity and overnight stays, as well as optimisation tasks of maximum coverage and p-median. It has been shown that the existing state observation system has limited spatial coverage, is focused mainly on industrial centres, does not cover resort and mountain destinations, and does not reflect peak seasonal loads associated with tourist flows. A two-level network architecture has been developed, combining three high-precision reference stations (urban, valley and industrial background) with an adaptive number of low-cost sensors (10-15 LCS) located in the centres of tourist demand and transport corridors. Weighted clustering of 3,725 tourist sites revealed the dominant role of the Polianytsia-Yaremcha resort valley and made it possible to identify a configuration of 12 sensors as a balanced option that minimises the average distance to

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monitoring points and ensures measurement redundancy in sensitive areas. The results obtained provide a basis for the phased deployment of an air quality monitoring network, the integration of environmental indicators into tourism management policy, environmental marketing of territories, and ESG reporting by tourism businesses

Keywords: environmental safety of tourism; atmospheric air quality; regional monitoring system; low-cost sensors; geospatial modelling; station placement optimisation; tourist destinations condition of forests

Introduction

The quality of atmospheric air is now recognised as an important factor in environmental safety and sustainable development, directly affecting not only public health but also the level of tourist attractiveness. Recent studies emphasise that clean air is not only a natural resource but also an economic asset on which the competitiveness of tourist destinations depends. Tourists are increasingly taking environmental conditions into account when choosing a holiday destination, so the availability and openness of data on air quality builds trust, reduces risks for visitors and enhances the image of the area.

The problem is that the current environmental reporting system covers only a limited list of pollutants, mainly from stationary sources, while international practice and the results of modern research emphasise the need to monitor fine particulate matter (PM_{2.5}, PM₁₀) and other specific pollutants. The impact of these microparticles, which are produced by the combustion of fuel in transport engines, heating systems in accommodation facilities and during food preparation in catering establishments, directly affects the health of the population, tourist attractiveness and environmental safety. Research by the World Health Organisation shows that even short-term exposure to PM_{2.5} causes exacerbation of respiratory and cardiovascular diseases, as well as a decrease in immunity, which is especially dangerous for children and the elderly. In its updated 2021 recommendations, the World Health Organisation has lowered the permissible concentrations of PM_{2.5}: the annual level from 10 to 5 µg/m³, and the daily level from 25 to 15 µg/m³.

The decision was based on a meta-analysis of more than 500 studies that confirmed significant risks even at concentrations below the previous standards (World Health Organization, 2021). In particular, a study by P.J. Landrigan *et al.* (2018), which covered data from 41 countries, showed an increase in mortality from cardiovascular diseases by 6.2%, respiratory diseases by 3.1%, and overall mortality by 4.1% with an increase in PM_{2.5} by every 10 µg/m³.

A study by the European Environment Agency (2020) found that visitors to urban and suburban tourist destinations are exposed to increased levels of fine particulate matter during peak seasons. An analysis conducted by S. Adamenko *et al.* (2024) in 25 European cities found that PM_{2.5} concentrations in tourist centres exceed background levels by 15-30% during peak hours, especially near popular attractions and in areas of heavy traffic. Tourists who spend most of their day outdoors are exposed to levels 1.5-2 times higher than the average for local residents, whose activities are more concentrated indoors.

A further contribution to the study of the impact of the air environment on tourists was made by A. Tobías *et al.* (2020). The study used mobile monitoring stations located in tourist areas of Barcelona. The results confirmed that even a short stay (2-3 hours) in conditions of elevated PM_{2.5} concentrations (>25 µg/m³) leads to significant physiological effects, including a decrease in lung function and an increase in inflammation markers. The most vulnerable groups were children under 12 and older people, who experienced a 7-12% decrease in peak expiratory flow

and an increase in C-reactive protein levels. The researchers emphasise that such changes pose a particular risk to tourists, as they often have limited access to medical care while travelling and may not identify the deterioration in their health as a result of air pollution.

A study by the European Environment Agency (2021) showed that 63% of tourists consider air quality when choosing a destination, and 78% are willing to change their travel plans if environmental conditions deteriorate. These results were confirmed by a study by I. Arbulú *et al.* (2021), which, based on data from 87 European cities, found a statistically significant correlation between air quality deterioration and a decline in tourist arrivals with a lag of 1-2 months. Family and “silver” tourism segments were particularly vulnerable to this factor, with a 17-23% drop in bookings following widespread media coverage of pollution incidents.

The air quality monitoring system is characterised by spatial and temporal limitations. Stationary monitoring stations are concentrated mainly in large cities and industrial regions, while tourist destinations in mountainous and rural areas remain outside the scope of regular observation. In addition, reports are generated on a quarterly or annual basis, which does not allow for the reflection of short-term peak loads characteristic of tourist flows. According to data from L.M. Arkhypova *et al.* (2025), tourist activity is highly seasonal (winter and summer peaks in the Carpathian region) and subject to daily fluctuations, during which pollutant concentrations significantly exceed average annual levels, particularly during peak hours, periods of mass events or unfavourable weather conditions. Such episodes have a significant impact on tourists' subjective perception of the destination and their willingness to return, but they become statistically invisible in aggregated annual data.

Another systemic limitation is the lack of differentiation of pollution sources in reporting by economic sector. Tourism generates specific pollution patterns due to the intensive use of private

and bus transport, increased energy consumption in accommodation and catering establishments, and increased volumes of household waste. However, these sources often fall into different reporting categories or are not recorded when they do not exceed threshold values. In particular, a significant number of vehicles serving tourists are classified as private transport and are not included in industry statistics on tourism. Similarly, small and medium-sized accommodation establishments use individual heating systems, whose emissions are not subject to systematic monitoring. Such fragmentation of data creates “blind spots” in the analysis of the environmental impact of tourism and highlights the need to implement integrated approaches to monitoring that take into account the complex nature of the interaction between tourism and the environment.

The aim of the article was to provide a scientific justification for approaches to the formation of a regional network for monitoring air quality in tourism-oriented areas. The scientific novelty lies in the development of a comprehensive approach to the formation of a network for monitoring air quality in tourist regions, based on the integration of geospatial clustering of tourist facilities, tourism capacity indicators and European requirements for the representativeness of monitoring networks, as well as in substantiating the functional structure of such a network as a tool for environmental safety and tourism load management.

Materials and Methods

The study was conducted during 2024-2025. A set of complementary methods was applied. Formal legal and comparative legal methods were used to analyse European and national requirements for the organisation of air-quality monitoring systems, as well as to identify methodological and regulatory constraints on their implementation at the regional level in accordance with the provisions of European Union directives in the field of air quality and Ukraine's obligations under the EU-Ukraine Association

Agreement (Verkhovna Rada of Ukraine, 2014; European Union, 2008; 2024).

Spatial analytical methods were implemented in a geographic information system environment to process and integrate the coordinates of tourist facilities, administrative boundaries of territorial communities, the transport and road network, and the orographic characteristics of the area. The methodological basis of the study was the integration of geospatial data covering the spatial distribution of tourist points of interest (POIs) according to OpenStreetMap data, together with proxy indicators of tourist capacity, indicators of tourist overnight stay (TN), administrative boundaries of territorial communities, the configuration of transport infrastructure, topographic characteristics of the terrain, and, where available, information on prevailing wind directions. This corresponded to European practices of spatial analysis of environmental pressures and risks (European Environment Agency, 2020; 2021).

The algorithmic core of the optimisation was formed on the basis of geospatial methods, with priority given to the practical interpretability of the results. The methodological framework included weighted k-means clustering based on criteria of tourist capacity and intensity of use to identify the cores of tourist demand and determine candidate sensor locations; the p-median and Maximum Coverage Problem models for the optimal selection of a subset of points under given constraints on the number of sensors and the minimum distance between them; analysis of zones of responsibility through the construction of Voronoi diagrams; and mapping of coverage heat maps taking into account the effective operating radius of the measuring equipment. This approach is consistent with contemporary methods for designing air-quality monitoring networks and using low-cost sensors (Dechezleprêtre *et al.*, 2019; Neis *et al.*, 2023).

The optimality criteria for the network structure included maximising the share of tourist capacity within the coverage radius of the sensors, minimising the average distance from

tourist facilities to the nearest monitoring post, and ensuring balanced representation of different environment types, including resort valleys, urban and industrial background locations, and high-altitude reference points, in accordance with the requirements of European and international environmental regulation (European Union, 2008; World Health Organization, 2021).

The proposed approach ensured compliance with European practices of scientifically grounded design of air-quality monitoring networks and created an information basis for integrating environmental data into regional policies for managing tourist pressure during peak seasons, communicating environmental conditions to visitors, and developing ESG reporting for tourism businesses in line with the strategic priorities of Ukraine's state environmental policy up to 2030 (Law of Ukraine No. 2697-VIII, 2019; European Environment Agency, 2021).

To solve the problem of optimal placement of the monitoring network in tourist regions, the study applied a methodology based on the spatial distribution of tourist infrastructure facilities (POIs from OpenStreetMap) and aimed at determining the optimal placement of p low-cost sensors (LCS) and q reference monitoring stations. The target optimisation criteria were as follows:

1. ensuring representative spatial coverage of the main tourist clusters and zones of visitor concentration;
2. minimising the average accessibility distance from tourist demand points to the nearest sensors of the monitoring network;
3. taking into account technological and methodological constraints, such as the minimum permissible distances between neighbouring sensors and the balanced placement of monitoring points covering different functional zones (resort cores, urban and industrial background areas, as well as high-altitude reference sites).

This formulation of the problem makes it possible to create a scientifically grounded spatial network of environmental monitoring adapted to the specifics of tourist land use.

Figure 1 schematically presents the stages of the study on the optimal placement of the air-quality monitoring network. The following

set of spatial data was used to optimise the placement of air-quality monitoring stations (Table 1).

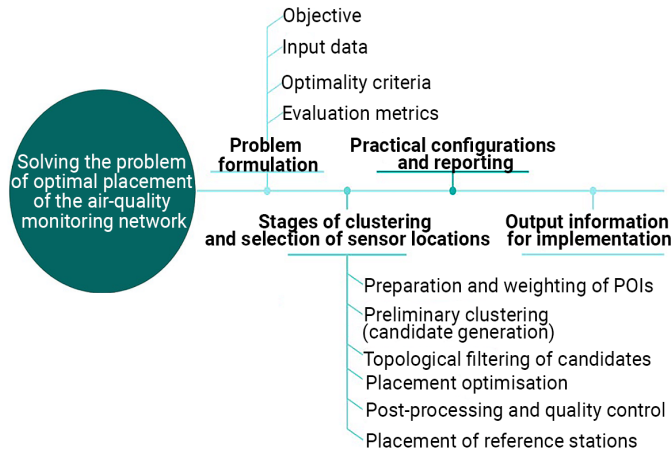


Figure 1. Scheme for conducting the study on the optimal placement of an air-quality monitoring network

Source: developed by the authors

Table 1. Structure of input spatial data and optimisation parameters for the air quality monitoring network

Data/parameter block	Designation	Content and characteristics
Set of tourist demand points	I	A set of spatially localised tourist points of interest (POIs) that generate demand for environmental monitoring
Spatial coordinates of POI	x_i, y_i	Geographical coordinates of each tourist point of interest
Capacity weighting factor	w_i	Capacity indicator of the facility, reflecting the number of beds, maximum throughput, or other relevant characteristics
Weight value in the absence of data	$w_i = 1$	The base value used in the absence of reliable information about capacity
Territorial affiliation attribute	-	The POI's affiliation with a specific territorial community or transport corridor, determined by the spatial connection method
Set of potential locations for station placement	J	A set of candidate points for the installation of monitoring stations
Generation of candidate locations	-	Automatic generation according to specified spatial and functional criteria
Spatial coordinates of locations	(X_j, Y_j)	Geographical coordinates of each potential station location
Monitoring network configuration parameters		
Effective coverage radius	r	Maximum range of a single monitoring station within which the representativeness of measurements is ensured (e.g. 2 km)
Minimum permissible distance between stations	dmin	Restriction that ensures spatial dispersion of the network and prevents excessive duplication of measurements (e.g., 2 km in valley areas)
Target number of local stations	p	Number of low-cost sensors selected from a set of alternatives {10; 12; 15} in accordance with budgetary and spatial constraints
Number of reference posts	q	Number of stationary reference stations for calibration and data verification, selected from a set {2; 3}

Table 1. Continued

Data/parameter block	Designation	Content and characteristics
Coverage quotas by functional zones		Minimum requirements for spatial representation of different types of territories within the monitoring network
Resort centres	-	Areas with maximum concentration of tourist demand
Transport corridors and leeward valleys	-	Areas of potential accumulation of pollutants along transport infrastructure
Urban background pollution areas	-	Urban locations without the dominant influence of individual sources
Industrial impact zones	-	Areas with local or point industrial emissions
High mountain areas	-	Reference areas for determining background concentrations of pollutants

Source: developed by the authors

To determine the optimal configuration of the monitoring network, two equivalent mathematical formulations are used: the Maximum Coverage Location Problem (MCLP) model and the p -median model (distance minimisation).

(A) Maximum Coverage Location Problem (MCLP). This model is aimed at maximising the weighted coverage of tourist demand points. The formalisation included:

► a proximity matrix $a_{ij} = 1[d(i,j) \leq r]$, where $d(i,j)$ – the distance between demand point i and potential location j , and r is the coverage radius;

► binary decision variables:

► $y_j \in 0,1$ – indicator of selecting location j ;

► $z_i \in 0,1$ – indicator of coverage of demand point i .

The objective function maximised weighted coverage:

$$\max \sum_{i \in I} \omega_i z_i \quad (1)$$

subject to the following constraints: $\sum_{j \in J} y_j = p$ (selection of exactly p locations), $z_i \leq \sum_{j \in J} a_{ij} y_j$; $\forall i$ (a point is considered covered if it lies within the radius of at least one selected location), $y_j \in \{0,1\}$, $z_i \in \{0,1\}$ binary variables).

(B) p-median model (distance minimisation).

An alternative formulation aimed at minimising the weighted distances between demand points and the nearest monitoring stations:

► assignment variables $x_{ij} \in 0,1$ – indicator that demand point i is served by location j ;

► binary site selection variables $y_j \in 0,1$.

The objective function minimised the weighted distance:

$$\min \sum_{i \in I} \sum_{j \in J} \omega_i \cdot d(i,j) \cdot x_{ij} \quad (2)$$

subject to the following constraints: $\sum_{j \in J} x_{ij} = 1$; $\forall i$ (each demand point is served by exactly one location), $x_{ij} \leq y_j$; $\forall i, j$ (a point can be served only by a selected site), $\sum_{j \in J} y_j = p$ (selection of exactly p locations), $y_j \in 0,1$, $x_{ij} \in 0,1$ (binary variables). To ensure the representativeness and functional balance of the network, additional constraints were introduced:

► quotas by functional zones: $\sum_{j \in G_g} y_j \geq L_g$ for each group g (resort cores, transport corridors, urban areas, etc.);

► minimum distance constraint: for pairs of sites (j,k) with distance $d(j,k) < d_{\min}$ the constraint $y_j + y_k \leq 1$, was imposed, preventing excessive concentration of stations.

For a comprehensive assessment of the quality of the obtained solutions, the following metrics are used:

1. Demand coverage ratio:

$$CR = \frac{\sum_i \omega_i \cdot 1[\min_j d(i,j) \leq r]}{\sum_i \omega_i}, \quad (3)$$

which reflects the share of weighted demand located within the coverage radius of at least one monitoring station.

2. Mean nearest distance:

$$MND = \frac{\sum_i \omega_i \cdot \min d(i,j)}{\sum_i \omega_i}, \quad (4)$$

which characterises the weighted average distance from demand points to the nearest stations.

3. Indicators of balance and reliability:

► variance and the Gini coefficient by the level of coverage of territorial communities;

► share of the territory with double coverage (to ensure redundancy);

► degree of compliance with quotas by functional station types;

► level of coverage of priority tourist clusters (Polianytsia, Yaremche territorial communities, etc.).

The comprehensive application of these criteria made it possible to form an optimal configuration of the monitoring network that ensures

maximum coverage of tourist demand while maintaining functional balance and spatial representativeness of the system. The database of tourist facilities was formed by extracting the following categories from OpenStreetMap (OSM). Accommodation establishments included objects with the tags `tourism = hotel`, `tourism = guest_house`, `tourism = apartment`, `tourism = hostel`, `tourism = camp_site`, `tourism = alpine_hut`, `tourism = chalet`. Where necessary, catering establishments with the tags `amenity = restaurant` and `amenity = cafe` were added to the database. The selection was carried out using geospatial queries that ensured comprehensive coverage of the tourist infrastructure of the study area. Tourist facilities are visualised in Figure 2.

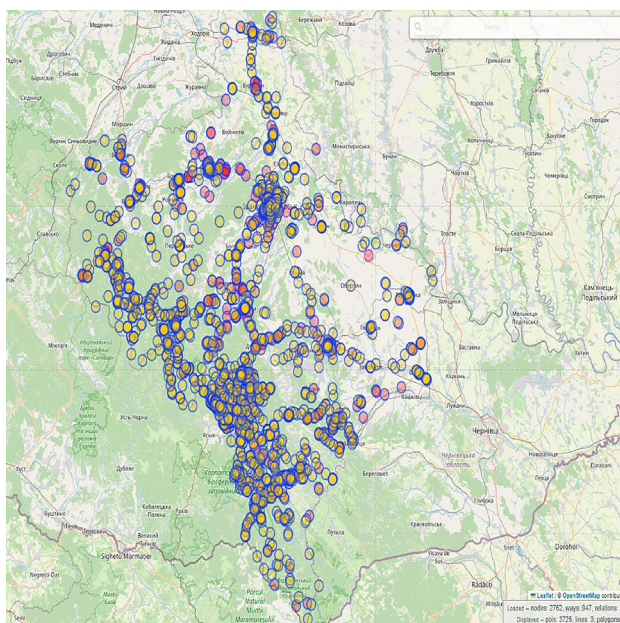


Figure 2. List of POIs for tourism and related industries from OpenStreetMap

Source: developed by the authors

As shown in Figure 2, 3,725 tourist facilities were selected within the territory of Ivano-Frankivsk Region that meet the conditions specified above (object categories). The process of optimising the placement of monitoring stations is based on a comprehensive analysis of

the spatial distribution of tourist infrastructure. Clustering was performed using a dataset of tourist points of interest (POIs) extracted from OpenStreetMap, including accommodation facilities (hotels, guest houses, apartments) and related infrastructure (campsites, mountain huts). To

ensure representativeness, differentiated weighting of objects was applied according to their capacity, using the attributes beds and capacity:persons; where these were absent, estimated values were calculated based on the number of rooms and camping pitches. To improve the model's robustness to extreme values, weight capping at the 99th percentile of the distribution was applied.

The spatial structure was determined using a weighted k-means algorithm with weighted k-means++ initialisation, which takes into account not only spatial proximity but also the significance of the facilities. The medoids of the resulting clusters were used as candidate points for the placement of monitoring stations. To prevent excessive concentration of sensors, a topological constraint of a minimum mutual distance between sites of $d_{\min} = 2$ km was applied, ensuring the spatial dispersion of the network.

Three alternative network configurations with different numbers of LCS were considered: $p \in \{10, 12, 15\}$. For each option, cartographic materials were developed, including cluster maps with the boundaries of territorial communities and Voronoi diagrams illustrating the zones of responsibility of each station.

Results and Discussion

The European Union's regulatory framework forms a comprehensive and hierarchically structured system of requirements for monitoring PM_{10} and $PM_{2.5}$ concentrations, as well as for ensuring the transparency, comparability and accessibility of environmental data. For a long time, Directive 2008/50/EC (European Union, 2008) was the key basic act in this area, which established the obligation of Member States to establish representative networks of fixed observation stations in zones and agglomerations, taking into account the population, level of urbanisation and spatial structure of pollution sources. Particular attention was paid in this legal act to the average exposure to $PM_{2.5}$, for the assessment of which it was envisaged to install at least one sampling point per million inhabitants, aggregated by

agglomerations and additional urban areas with a population of over 100,000, which was in line with the concept of urban background monitoring and a focus on assessing the impact of pollution on public health. The further evolution of European environmental regulation took place in the context of the implementation of the European Green Deal, within which the European Commission presented a proposal in 2022 to revise the current directive on ambient air quality (European Commission, 2022). This initiative was aimed at gradually bringing the limit and target values for pollutant concentrations closer to the recommendations of the World Health Organisation, as well as strengthening the requirements for the spatial density and functional differentiation of monitoring networks, particularly in regions with high tourist traffic and seasonal peaks of anthropogenic impact.

The new approach was enshrined in law in 2024 with the adoption of Directive (EU) 2024/2881 (European Union, 2024) in its recast version, which replaces Directive 2008/50/EC (European Union, 2008) as of 12 December 2026 and introduces updated air quality standards, improved assessment methods, expanded modelling and forecasting requirements, and mandatory mechanisms for open access to environmental information for the public and public authorities. The change in the regulatory paradigm reflects the European Union's strategic course towards integrating environmental safety, public health and increasing the competitiveness of tourist destinations within the framework of sustainable development.

The implementation of European environmental monitoring standards in Ukraine is carried out in the context of fulfilling international obligations set out in the Association Agreement between Ukraine and the European Union (Verkhovna Rada of Ukraine, 2014). An important aspect of this process is the harmonisation of national legislation with the *acquis communautaire* in the field of environmental protection. Law of Ukraine No. 2697-VIII (2019) defines the development of

an atmospheric air monitoring system as a strategic priority of state environmental policy, which directly correlates with the provisions of Directive 2008/50/EC (European Union, 2008) on the assessment and management of atmospheric air quality.

The practical mechanism for implementing these standards is enshrined in Resolution of the Cabinet of Ministers of Ukraine No. 827 (2019). The document defines methodological approaches to the creation of zones and agglomerations for monitoring, including areas with high tourist activity. It regulates the deployment of a network of automated observation posts equipped with modern devices for measuring concentrations of fine particulate matter $PM_{2.5}$ and PM_{10} , which meets the technical and procedural requirements

of the European Union. The implementation of these provisions ensures the gradual approximation of the Ukrainian environmental monitoring system to European standards, forming the basis for effective air quality management in tourist-attractive regions and improving the environmental safety of the population.

However, the gap between regulatory requirements and their actual implementation remains significant, especially in tourist regions, where the lack of systematic monitoring hinders effective environmental risk management and reduces the competitiveness of destinations compared to their European counterparts. Open sources of data on atmospheric air quality are shown in Table 2.

Table 2. Open sources of data on air quality

Source category	Resource name	Brief description
Global aggregators and APIs	OpenAQ	The largest open data aggregator for $PM_{2.5}$, PM_{10} , NO_2 , O_3 , SO_2 concentrations; REST-API v3, archive on AWS; suitable for multi-country research and prototyping
	World Air Quality Index (WAQI)	Global map and API with AQI and concentration indicators based on official stations and partner networks
European platforms	EEA Air Quality e-Reporting	Official downloads of time series and statistics for EU countries and partners; station data is validated; visualisation portal available
	Copernicus Atmosphere Monitoring Service (CAMS)	Open analyses and forecasts for Europe and the world; data provided via Atmosphere Data Store (CDS API)
US sources	AirNow (US EPA)	Real-time API and forecasts for the US, Canada, and Mexico; includes AQI and station metadata
	EPA AQS API	Access to the Air Quality System database with retrospective, verified data
Ukraine (official and public initiatives)	Ukrainian Hydrometeorological Centre (UHMC)	Daily air pollution indicators by city in table format, available for download
	SaveEcoBot (SaveDnipro)	Aggregator of official and public sensors; open API and CSV files with hourly $PM_{2.5}$, NowCast, and meteorological data series; integrated into an open data portal
Public LCS networks (low-cost sensors)	Sensor.Community (Luftdaten)	Fully open network of public sensors; map and API for PM measurements; ability to connect own sensors
	openSenseMap (senseBox)	Open sensor station platform; REST API, bulk uploads; supports PM measurements
	PurpleAir	Extensive LCS network; official API and access to historical data
Model and combined services	Open-Meteo Air Quality API	Free forecasts and reanalyses based on CAMS for Europe and the world; returns concentrations of $PM_{2.5}$, PM_{10} , NO_2 , O_3 , SO_2 , NH_3 ; convenient for basic assessments and gap filling

Source: developed by the authors

Compared to the European Union, which has a multi-level air quality monitoring system,

Ukraine lags significantly behind in terms of network density and organisational structure. The

European model is based on regulatory reference stations of various types: urban background, traffic and industry. These stationary points form a highly accurate infrastructure framework that ensures data reliability and reproducibility. This framework in the EU is supplemented by thousands of low-cost sensors integrated into municipal networks and citizen science initiatives, which creates high spatial detail and temporal continuity of observations, allows for reanalysis and

forecasting in combination with meteorological models, and ensures regular calibration of data from LCS sensors relative to reference stations. The result is a high level of trust in environmental information among the public and the scientific community, as evidenced by the integration of such data into open portals and APIs (Fig. 3). It is the combination of official and public tools that ensures the systematic and consistent quality of European environmental monitoring.

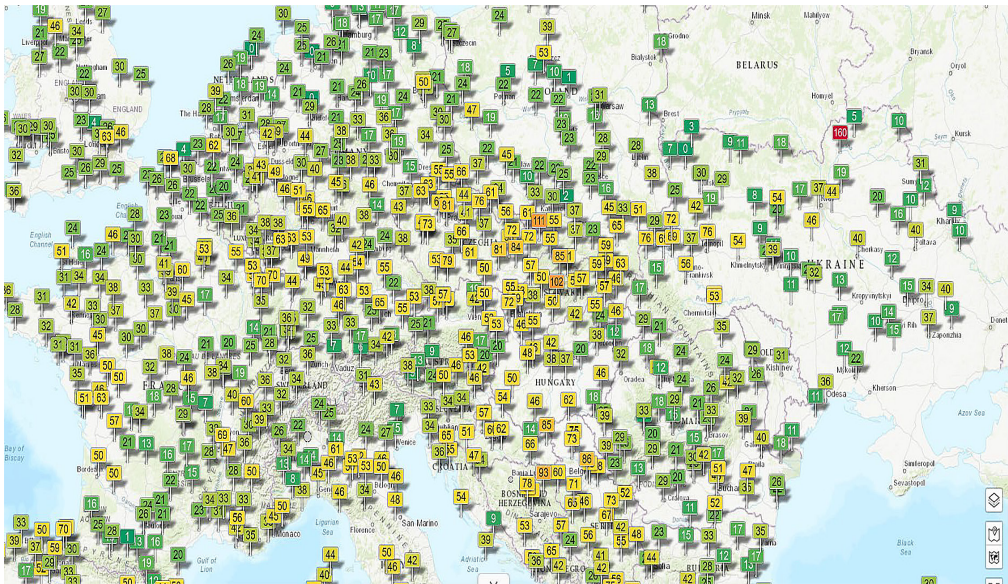


Figure 3. Density of the air quality monitoring system in the EU

Source: developed by the authors based on data of World's Air Pollution (n.d.)

In Ukraine, however, there has historically been limited funding, fragmentation of standards, uneven geographical coverage outside regional centres, a lack of regular LCS calibration, and a lack of methodological integration of public data with official data. Military risks and damage to infrastructure have been additional factors. Figure 4 shows that there is no information available on air quality in tourist destinations in the Carpathian region. That is why local initiatives by tourism operators – installing low-cost sensors linked to reference points, opening up data and basic analytics (seasonality,

peak hours, correlation with occupancy) – have a double payoff. They improve risk management and service quality at the facility, while also filling gaps in the state network in tourist clusters (Polianytsia-Yaremche-Vorokhta, etc.), where environmental conditions change rapidly and unevenly across the region. As a result, the region receives sufficient data for forecasting, targeting environmental interventions and honest communication with guests, which is a direct investment in the sustainability and competitiveness of the tourism product. Analysis of the clustering results reveals stable spatial patterns

that persist over a wide range of p parameters: The “Carpathian resort core” is steadily forming as the largest cluster in terms of total capacity along the Polianytsia-Tatariv-Vorokhta-Yaremche axis, reflecting the actual distribution of accommodation and services and at the same time demonstrating a high degree of consistency with the predefined TN indicators.

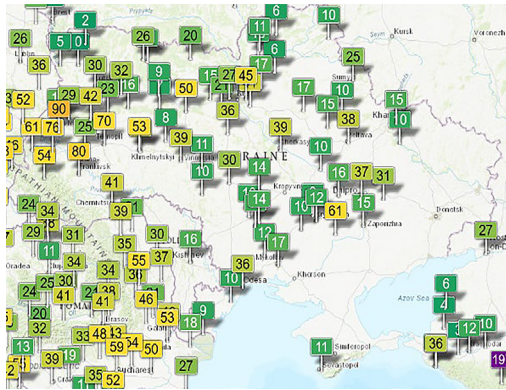


Figure 4. Density of the air quality monitoring system in Ukraine

Source: developed by the authors based on data of World's Air Pollution (n.d.)

Overlaying heat maps of tourist load on the configuration of spatial clusters of tourist POIs demonstrates a high level of consistency between demand intensity and clustering structure (Fig. 5-7). The maximum values of tourist load are concentrated in the resort core nodes, in particular in the Bukovel-Polianytsia agglomeration, as well as in the settlements of Tatariv, Vorokhta and Yaremche, which form a functionally linked system with a high density of tourist facilities. Within the satellite microclusters represented by Mykulychyn, Yablunytsia and Deliatyn, a downward gradient of demand is observed, while the peripheral areas are characterised by minimum values of the indicators. This spatial distribution reflects the hierarchical organisation of the tourist space, with the resort core dominating and the intensity of activity gradually decreasing towards the periphery.

ROI clusters + boundaries
of territorial communities

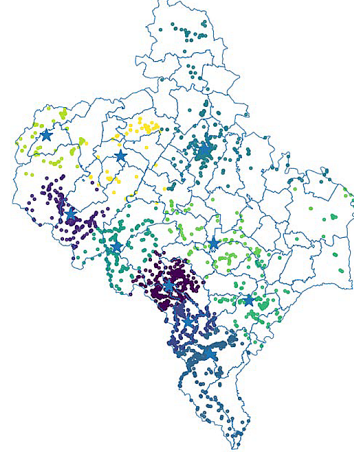


Figure 5. Clusters of tourist POIs with territorial community boundaries

Note: configuration $p = 10$; stars indicate the recommended LCS installation points (medoids of weighted clusters with a minimum mutual distance of 2 km). The spatial framework reflects the dominance of the Polianytsia–Yaremche resort core and its “gateways”, with background points in urban and industrial nodes

Source: developed by the authors

ROI clusters + boundaries
of territorial communities – $p = 12$

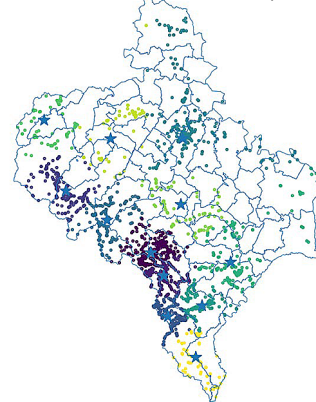


Figure 6. Clusters of tourist POIs with territorial community boundaries

Note: network expansion reduces gaps in corridors “downwind” from the core and improves control in the southern sector (configuration $p = 12$).

Source: developed by the authors

ROI clusters + boundaries
of territorial communities – $p = 15$

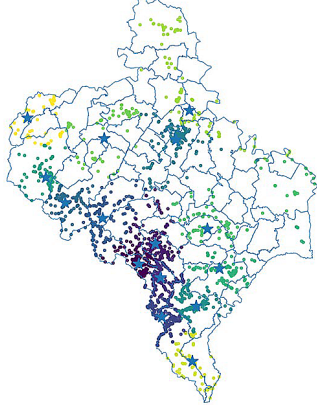


Figure 7. Clusters of tourist POIs
with territorial community boundaries

Note: additional points ensure more even coverage of peripheral areas, while maintaining the priority of the resort valley; configuration $p = 15$

Source: developed by the authors

The stability of the selected core is confirmed by the preservation of stable centres of gravity of clusters and insignificant changes in the configuration of boundaries with variations in parameter p (compare Figures 5-7). Such invariance of the spatial structure indicates the presence of a pronounced agglomeration effect, caused by a combination of tourist specialisation, transport accessibility and the valley morphology of the territory. The spatial framework correlates with the linear organisation of transport infrastructure along the H-09 motorway corridor and railway line, which form the main axis of concentration of tourist flows and related facilities. A comparison of configurations with different numbers of clusters demonstrates the evolution of the spatial coverage of the network of observation points. In the $p = 10$ configuration, a basic spatial framework is formed with a clearly defined resort core and “gateways” to it, while background points tend to gravitate towards urban and industrial hubs (Fig. 5). Increasing the number of clusters to $p = 12$ reduces spatial gaps in transport and valley corridors, particularly in directions located “downwind” from the main

core, and increases control in the southern sector of the study area (Fig. 6). The $p = 15$ configuration provides more uniform coverage of peripheral areas without losing the priority of the resort valley, which indicates the possibility of scaling the network taking into account the territorial heterogeneity of tourist load (Fig. 7). The analysis of areas of responsibility constructed using the Voronoi method details the functional logic of the spatial organisation of the monitoring network (Figs. 8-10).

POI clusters (Voronoi)- $p = 10$



Figure 8. Areas of responsibility (Voronoi) for $p = 10$

Source: developed by the authors

POI clusters (Voronoi)- $p = 12$

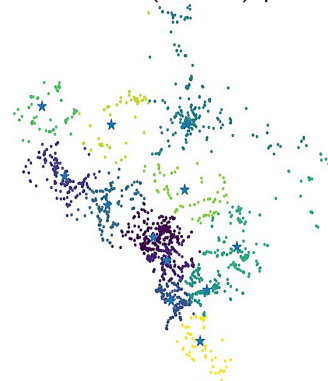


Figure 9. Areas of responsibility (Voronoi) for $p = 15$

Note: there is a finer division of polygons in the high-capacity zone (Polianytsia-Yaremcha core), which reduces the average distance from the POI to the sensor

Source: developed by the authors

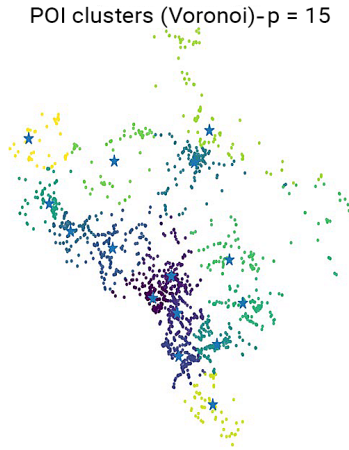


Figure 10. Areas of responsibility (Voronoi) for $p = 15$

Note: the proportion of territory with double coverage in sensitive corridors is increasing, which improves signal reliability in adverse weather conditions

Source: developed by the authors

The basic configuration is characterised by polygons elongated along valleys with minimal overlap, corresponding to the pilot observation framework (Fig. 8). With an increase in the number of points to $p = 12$, a finer division of polygons is observed in the high-capacity area of the Polianytzia-Yaremche resort core, resulting in a reduction

in the average distance from tourist POIs to control points (Fig. 9). Further densification of the network to $p = 15$ leads to an increase in the proportion of areas with double coverage in the most sensitive transport and recreational corridors, which increases the reliability of signal reception in adverse weather conditions and forms a reserve of spatial stability for the monitoring system (Fig. 10). Analysis of Voronoi diagrams (Fig. 8-10) demonstrates the evolution of the “areas of responsibility” of each site as their number increases. At $p = 10$, the polygons have an elongated shape along river valleys, reflecting the orographic influence on the distribution of tourist infrastructure. When the number of sites increases to $p = 12$ and $p = 15$, fragmentation of polygons is observed in areas of increased tourist capacity, which leads to a decrease in the average distance from points of interest to the nearest sensor and increases the redundancy of the system due to partial overlap of monitoring areas. In the base configuration ($p = 10$), most locations are concentrated within the main tourist valley and on key transport approaches to it, while peripheral points provide monitoring of the urban background (Ivano-Frankivsk, Kolomyia) and industrial and transport hubs, which is necessary for calibration and control of background concentrations (Table 3).

Table 3. Recommended LCS points (configuration $p = 10$)

Number of POIs in cluster	Total capacity (cond. units)	Coordinates (lon)	Coordinates (lat)	LCS number	Role	Cluster centre	Sector
767	931,000	24.501	48.390	1	resort core	Polianytsia	southern
349	470,000	24.753	48.114	2	high-rise background	Verkhovyna	southeastern
244	425,000	23.902	48.682	3	industrial background	Kalush	western
338	424,000	24.618	48.245	4	resort core	Vorokhta	southeastern
384	406,000	24.719	48.943	5	urban background	Ivano-Frankivsk	northeastern
232	331,000	24.182	48.550	6	resort core	Polianytsia	western
156	167,000	24.989	48.332	7	corridor/valley “downwind”	Kosiv	southeastern
121	121,000	24.776	48.563	8	resort core	Yaremche	eastern
101	112,000	23.754	49.000	9	industrial background	Kalush	northwestern
71	82,000	24.208	48.916	10	industrial background	Kalush	northwestern

Source: developed by the authors

Expanding the network to $p=12$ adds coverage in the southern and eastern sectors of the region, corresponding to the directions of the catchment basins from the resort core and the main transit corridors (Table 4). The maximum configuration

($p = 15$) provides a more uniform presence in the peripheral areas of the mountain and foothill belts and enhances control of the “high-altitude background”, which is important for understanding the vertical stratification of pollutants (Table 5).

Table 4. Recommended LCS points (configuration $p = 12$)

Number of POIs in cluster	Total capacity (cond. units)	Coordinates (lon)	Coordinates (lat)	LCS number	Role	Cluster centre	Sector
618	762,000	24.482	48.403	1	resort core	Polianytsia	southern
378	452,000	24.570	48.298	2	resort core	Vorokhta	southeastern
244	425,000	23.902	48.682	3	industrial background	Kalush	western
385	407,000	24.700	48.917	4	urban background	Ivano-Frankivsk	northeastern
256	330,000	24.598	48.113	5	resort core	Vorokhta	southern
219	318,000	24.182	48.550	6	resort core	Polianytsia	western
162	243,000	24.831	48.162	7	high-altitude background	Verkhovyna	southeastern
178	178,000	25.028	48.360	8	corridor/valley “downwind”	Kosiv	eastern
101	112,000	23.754	49.000	9	industrial background	Kalush	northwestern
84	84,000	24.687	48.621	10	resort core	Yaremche	northeastern
70	81	24.20759	48.916028	11	industrial background	Kalush	northwestern
68	77,000	24.788	47.927	12	high-altitude background	Verkhovyna	southeastern

Source: developed by the authors

Table 5. Recommended LCS points (configuration $p = 15$)

Number of POIs in cluster	Total capacity (cond. units)	Coordinates (lon)	Coordinates (lat)	LCS number	Role	Cluster centre	Sector
375	455,000	24.442	48.353	1	resort core	Polianytsia	southern
351	427,000	24.553	48.445	2	resort core	Yaremche	southeastern
295	357,000	24.590	48.292	3	resort core	Vorokhta	southeastern
256	330,000	24.598	48.113	4	resort core	Vorokhta	southern
219	307,000	24.198	48.559	5	resort core	Polianytsia	western
277	299,000	24.694	48.910	6	urban background	Ivano-Frankivsk	northeast
150	297,000	23.942	48.629	7	industrial background	Kalush	western
164	245,000	24.831	48.162	8	high-altitude background	Verkhovyna	southeast
112	157,000	23.811	48.742	9	industrial background	Kalush	western
118	118,000	24.989	48.332	10	corridor/valley “downwind”	Kosiv	eastern
115	115	24.7851614	49.040794	11	urban background	Ivano-Frankivsk	northeast

Table 5. Continued

Number of POIs in cluster	Total capacity (cond. units)	Coordinates (lon)	Coordinates (lat)	LCS number	Role	Cluster centre	Sector
109	109,000	24.907	48.511	12	urban background	Kolomyia	eastern
81	92	23.6862807	49.0080632	13	industrial background	Kalush	northwest
79	90,000	24.208	48.916	14	industrial background	Kalush	northwest
62	71,000	24.805	47.912	15	high-altitude background	Verkhovyna	southeast

Source: developed by the authors

The proposed methodology and optimisation results provide a scientifically grounded basis for the phased deployment of an air-quality monitoring network that corresponds to the spatial structure of tourist demand and accounts for orographic features. To ensure the metrological reliability of the regional air-quality monitoring network, it is advisable to establish a core of three permanent high-precision reference stations intended for the calibration and verification of data obtained from LCS. The spatial placement of the reference stations should correspond to different environmental types and reflect the functional diversity of the region, thereby ensuring the representativeness of measurements and enabling differentiated interpretation of monitoring results. A reference station of the “urban background” type is appropriate for placement within the city of Ivano-Frankivsk, in an area distant from intensive traffic flows and industrial facilities, for example within a residential district or on a university campus. The functional purpose of such a station is to record background concentrations of pollutants in the urban environment, provide a baseline calibration point for the LCS network, and support long-term analysis of air-quality dynamics in the regional administrative centre. The availability of stable power supply, telecommunications infrastructure, and physical security enhances the reliability of observations, while location within an educational environment creates additional opportunities for integrating monitoring into scientific and educational programmes.

A reference station of the “valley background” type should be located within the Polianytsia–Yaremche basin, at a representative point in the lower part of the valley that characterises the typical exposure conditions of the resort zone. The purpose of such a station is to monitor background concentrations of pollutants in the region’s key tourist location, analyse the spatial redistribution of impurities under mountain orographic conditions, and record episodes of temperature inversion characteristic of valley environments. The resulting data form the basis for assessing seasonal fluctuations in air quality associated with tourist loads and enable the co-location and calibration of LCS during peak recreational periods.

A reference station of the “industrial background” type is advisable for placement near the town of Burshtyn, in an area situated downwind of the Burshtyn thermal power plant but at a distance sufficient to register dispersed rather than local emissions. The functional significance of such a station lies in separating the industrial component of pollution from tourism-related impacts, monitoring the region’s largest stationary emission source, and providing a control baseline for analysing transboundary pollutant transport. Industrial background data enable comparative analysis with tourist zones and serve as an informational basis for evaluating the effectiveness of environmental protection measures.

The proposed configuration of reference stations forms a comprehensive calibration

framework for the entire low-cost sensor network, enhances the reliability of spatio-temporal air-quality assessments, and creates the preconditions for scientifically grounded interpretation of monitoring results in the context of interactions between tourism activities and the atmospheric environment of the region.

The results of weighted clustering of tourist points of interest (POIs) extracted from OpenStreetMap indicate the spatial dominance of the Polianytsia–Yaremche resort valley, where the majority of accommodation capacity and related infrastructure is concentrated. The identified distribution of tourist demand justifies the prioritised placement of the low-cost sensor network within this zone. A comparative analysis of alternative configurations shows that the option with twelve stations ($p = 12$) provides an optimal compromise between investment costs and the quality of spatial coverage, significantly reducing the average distance from tourist sites to the nearest monitoring point in environmentally sensitive corridors located under the influence of airflows from the main centres of recreational activity. Expanding the network to fifteen stations ($p = 15$) increases system reliability through partial overlap of responsibility zones and improves monitoring of peripheral areas, which is critically important for the timely detection of pollution episodes during peak tourist seasons.

The integration of background monitoring points in urban and industrial areas is a methodologically necessary condition for calibrating low-cost sensor data and correctly differentiating tourism-related impacts from general anthropogenic loads. The coordinates of the optimal location of stations and the defined zones of their spatial responsibility are presented in a reproducible format in the form of software scripts and CSV files, which ensures the transparency of the methodology and the readiness of the results for practical validation during a micro-situational survey of potential locations. As a result, a network configuration of three permanently operating reference stations and an optimised number of LCSs

is proposed, capable of ensuring the metrological reliability, analytical depth and practical applicability of the air quality monitoring system in the tourist regions of the Ivano-Frankivsk region.

A summary of the results of recent empirical studies confirms a stable and statistically significant relationship between the level of atmospheric pollution and the spatial-temporal dynamics of tourist flows. In particular, the work of Y. Wang *et al.* (2023) demonstrates that the transparency of environmental information is an independent factor in the formation of tourist mobility, influencing the redistribution of demand between destinations. The public disclosure of data by F. Neirotti *et al.* (2020) on air quality has created competitive advantages for areas with low concentrations of pollutants and, at the same time, reduces the attractiveness of regions where environmental reporting is fragmentary or unavailable. Econometric estimates indicate a direct correlation between pollutant concentrations and the sensitivity of tourist demand to information transparency, which provides a scientific basis for institutional investment in monitoring systems and digital platforms for environmental communication at the destination level.

An in-depth analysis of tourist behaviour data conducted by Y. Yang *et al.* (2022) based on millions of TripAdvisor user reviews complements macroeconomic conclusions with micro-level evidence. The negative and statistically significant relationship between PM_{2.5} concentrations and tourist attraction ratings confirms that air pollution directly affects the subjective perception of the tourist experience. The use of panel regression models with spatial and seasonal controls minimises the risk of biased ratings and allows the decline in tourist demand to be interpreted as a result of environmental pressure rather than confounding factors. The systematisation of results in the review by C. Eusébio *et al.* (2021) demonstrates the conceptual consistency of scientific conclusions in different regional and methodological contexts. The negative impact of air quality deterioration can be seen not only in the reduction

in the number of tourist arrivals, but also in the reduction in the length of stay and the level of tourist satisfaction. In this interpretation, atmospheric air monitoring is not an auxiliary technical tool, but a component of strategic management of tourist demand and destination sustainability.

Macro-level empirical estimates by S.A. Churchill *et al.* (2022) for a sample of G20 countries for 1995-2014 confirm the systemic nature of environmental determinants of international tourism. Increases in PM_{2.5} and CO₂ concentrations are associated with a statistically significant reduction in international tourist arrivals, with developing countries showing greater sensitivity to environmental degradation. The results indicate an asymmetric distribution of environmental risks in the global tourism space and strengthen the argument for preventive environmental policies in regions with high dependence on tourism. Regional studies complement the overall picture by capturing the bidirectional nature of the interaction between tourism and the atmospheric environment. An analysis by M. Robaina *et al.* (2020) using European countries as an example shows that air quality degradation reduces tourist flows, while peak tourist activity can be a factor in the deterioration of local environmental indicators. This interdependence confirms the limitations of one-dimensional approaches to tourism management and highlights the need to integrate environmental constraints into spatial and seasonal planning of tourism activities. The results of Y. Tan *et al.* (2022), obtained using mobile tracking and PCSE assessment, expand the analytical framework by demonstrating the significant impact of air quality at both tourist destinations and points of departure. The review by S. Wang *et al.* (2024) added an economic dimension, demonstrating that in most cases the benefits of reducing fine particulate matter concentrations outweigh the costs of environmental interventions. For tourist destinations, these results mean not only reduced health risks, but also increased competitiveness and stability of tourist demand.

Compared to other studies, the current study emphasises the importance of integrating the public into the air quality monitoring process, as confirmed by the work of H. Relvas *et al.* (2025), which highlights the key role of involving local residents and tourists in improving the accuracy and timeliness of data collection. This is consistent with the findings of the current study, where the use of low-cost sensors in tourist areas contributes to improved monitoring and effective management of environmental risks. Also important is the work of N. Song & Y. Zhang (2025), which shows how environmental pollution affects tourist flows, particularly during peak tourist activity. The current study confirms this by applying geospatial methods to optimise the placement of monitoring stations in the most intensively visited tourist clusters, taking into account seasonal fluctuations in air pollution. Overall, the results of the current study make a significant contribution to the development of air quality monitoring methodology, taking into account both tourist activity and seasonal changes in pollution, allowing for more accurate forecasts and more effective management of environmental risks in tourist regions.

Compared to the study by I. Logothetis *et al.* (2025), which focuses on optimising air quality monitoring and waste management for sustainable island development, the current study extends this approach by applying geospatial models to create an air quality monitoring network in tourist regions. The study by I. Logothetis *et al.* focused on the integration of various aspects of environmental management, particularly in the context of small islands with limited infrastructure for air pollution control. However, in contrast to this, the current study proposes a more complex monitoring network structure that includes both stationary and low-cost sensors for broader coverage of high-traffic tourist areas. The current study also focuses on the specifics of tourist regions, where environmental pollution varies depending on seasonality and the intensity of tourist flows, which is an important aspect not covered in the work of I. Logothetis *et al.* Taking these seasonal

fluctuations into account is important for ensuring a comprehensive approach to monitoring and managing environmental risks in such regions, which makes the approach of the current study particularly relevant for tourist areas.

The economic feasibility of investments in pollution control is also confirmed in the analytical work of A. Dechezleprêtre *et al.* (2019), which shows that the benefits of environmental policies in the European context are comparable to or higher than the costs, even without accounting for the full range of social effects. Together with the findings of the systematic review by I.B. Bacos *et al.* (2024), this forms an understanding of air-quality monitoring as a “soft” infrastructure factor which, without substantial capital investment, can significantly influence tourist behaviour and the long-term competitiveness of destinations. An additional argument in favour of the economic viability of investments in the control and monitoring of atmospheric air pollution is provided by the study of X. Wu *et al.* (2020), which analysed the relationship between long-term exposure to fine particulate matter $PM_{2.5}$ and COVID-19 mortality rates across the United States. Based on an ecological regression model, the authors show that even a slight increase in average annual $PM_{2.5}$ concentrations is statistically significantly associated with higher mortality, indicating substantial hidden socio-economic losses linked to chronic air pollution. The study emphasises that the effects of pollution manifest themselves through the burden on health care systems, reduced population resilience to epidemiological risks, and increased indirect economic costs. At the same time, the authors critically outline the limitations of the environmental approach, emphasising the need for high-quality, spatially detailed air quality monitoring data for the correct interpretation of results. In this context, monitoring systems are seen as part of a preventive environmental policy that can reduce long-term social and economic losses, even if the direct costs of deploying them are relatively modest. The practical dimension of implementing such approaches is detailed in the work of P. Neis *et al.* (2023), which

proves that low-cost sensors provide an acceptable level of reliability provided that calibration and operating protocols are followed. In tourist regions with complex terrain, the use of LCS technologies allows the creation of dense observation networks that form a spatially detailed picture of air quality and open up new opportunities for environmentally oriented management of tourist activity.

Summarising the above results, air quality is a key factor in safety and comfort for tourists, influencing their choice of destination, travel time parameters and the nature of recreational activities. The availability of data on $PM_{2.5}$, PM_{10} , NO_2 and ozone concentrations reduces information asymmetry between tourists and market operators, builds trust in destination management practices and strengthens the case for the implementation of local, transparent and scientifically sound air quality monitoring systems.

Conclusions

The study confirmed that the formation of a regional system for monitoring and managing the environmental safety of tourism is a necessary prerequisite for ensuring the sustainable development of tourist destinations and increasing their competitiveness. The results obtained demonstrate the limitations of the existing air quality monitoring system in terms of spatial coverage, temporal resolution, and the ability to record the impact of tourist load, especially in resort and mountain areas of the Ivano-Frankivsk region. The proposed approach to designing a monitoring network, based on a combination of high-precision reference stations and a network of low-cost sensors, ensures the metrological reliability of measurements and, at the same time, high spatial detail of data. The use of geospatial clustering of tourist sites and optimisation models for station placement made it possible to justify the priority of the Polianytsia-Yaremcha resort valley and determine the optimal network configurations that minimise the average distance to monitoring points and increase the sensitivity of the system to peak seasonal loads.

The results of the study are consistent with current international scientific findings on the impact of air quality and information transparency on tourist demand and visitor behaviour. The methodology developed provides an analytical basis for integrating environmental data into regional tourism management policies, communication with tourists, and management decisions in the field of environmental safety. Further research should focus on empirical validation of the proposed network configuration based on a pilot deployment of sensors, expanding the range of monitored pollutants, taking into account the

specifics of tourism activities, as well as developing models for forecasting short-term risks for tourists during periods of peak load and adverse weather conditions.

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Conflict of Interest

None.

References

- [1] Adamenko, S., Arkhypova, L., Adamenko, Y., Moskalchuk, N., Glibovytska, N., & Chupa, V. (2024). Patterns of PM10 particles change in the atmospheric air of Ivano-Frankivsk city. *IOP Conference Series: Earth and Environmental Science*, 1415, article number 012002. doi: [10.1088/1755-1315/1415/1/012002](https://doi.org/10.1088/1755-1315/1415/1/012002).
- [2] Arkhypova, L.M., Adamenko, S.Y., Adamenko, Y.O., Kachala, T.B., & Kachala, S.V. (2025). Modeling the dependence of ambient air pollution on meteorological factors: A case study from Ukraine. *Journal of Physics: Conference Series*, 3153(1), article number 012021. doi: [10.1088/1742-6596/3153/1/012021](https://doi.org/10.1088/1742-6596/3153/1/012021).
- [3] Arbulú, I., Razumova, M., Rey-Maqueira, J., & Sastre, F. (2021). Can domestic tourism relieve the COVID-19 tourist industry crisis? The case of Spain. *Journal of Destination Marketing & Management*, 20, article number 100568. doi: [10.1016/j.jdmm.2021.100568](https://doi.org/10.1016/j.jdmm.2021.100568).
- [4] Bacos, I.B., Veres, C., Curta, P.A., Gabor, M.R., & Oltean, F.D. (2024). Impacts of air pollution on community well-being in the tourism sector: A comprehensive literature review. *Sustainability*, 16(23), article number 10752. doi: [10.3390/su162310752](https://doi.org/10.3390/su162310752).
- [5] Resolution of the Cabinet of Ministers of Ukraine No. 827 "Some Issues of State Monitoring in the Field of Atmospheric Air Protection". (2019, August). Retrieved from <https://zakon.rada.gov.ua/laws/show/827-2019-%D0%BF#Text>.
- [6] Churchill, S.A., Pan, L., & Paramati, S.R. (2022). Air pollution and tourism: Evidence from G20 countries. *Journal of Travel Research*, 61(2), 223-234. doi: [10.1177/0047287520977724](https://doi.org/10.1177/0047287520977724).
- [7] Dechezleprêtre, A., Rivers, N., & Stadler, B. (2019). *The economic cost of air pollution: Evidence from Europe (OECD Economics Department Working Papers No. 1584)*. Paris: OECD Publishing.
- [8] European Environment Agency. (2020). *Air quality in Europe – 2020 report*. Retrieved from <https://www.eea.europa.eu/publications/air-quality-in-europe-2020-report>.
- [9] European Environment Agency. (2021). *Air quality in Europe 2021*. Retrieved from <https://www.eea.europa.eu/en/analysis/publications/air-quality-in-europe-2021>.
- [10] European Union. (2008). *Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe*. Retrieved from <https://eur-lex.europa.eu/lexuri/sxkpe>.
- [11] European Commission. (2022). *Proposal for a directive of the European Parliament and of the Council on ambient air quality and cleaner air for Europe (recast) (COM(2022) 542 final)*. Retrieved from <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52022PC0542>.

- [12] European Union. (2024). *Directive (EU) 2024/2881 of the European Parliament and of the Council of 23 October 2024 on ambient air quality and cleaner air for Europe (recast)*. Retrieved from <https://lexcovery.com/2024/11/директива-ес-2024-2881-европейського-парлам>.
- [13] Eusébio, C., et al. (2021). The impact of air quality on tourism: A systematic literature review. *Journal of Tourism Futures*, 7(1), 111-130. doi: [10.1108/JTF-06-2019-0049](https://doi.org/10.1108/JTF-06-2019-0049).
- [14] Landrigan, P.J., et al. (2018). The Lancet Commission on pollution and health. *The Lancet*, 391(10119), 462-512. doi: [10.1016/S0140-6736\(17\)32345-0](https://doi.org/10.1016/S0140-6736(17)32345-0).
- [15] Logothetis, I., Kerchoulas, A., Kourkoumpas, D-S., Mitsotakis, A., & Grammelis, P. (2025). An integrated approach to air quality and waste management optimization for sustainable islands: A case study of Chalki, Southeast Aegean. *Sustainability*, 17(23), article number 10842. doi: [10.3390/su172310842](https://doi.org/10.3390/su172310842).
- [16] Neis, P., Warch, D., & Hoppe, M. (2023). Testing and evaluation of low-cost sensors for developing open smart campus systems based on IoT. *Sensors*, 23(20), article number 8652. doi: [10.3390/s23208652](https://doi.org/10.3390/s23208652).
- [17] Neirotti, F., Noussan, M., & Simonetti, M. (2020). Evaluating the emissions of the heat supplied by district heating networks through a life cycle perspective. *Clean Technologies*, 2(4), 392-405. doi: [10.3390/cleantechnol2040024](https://doi.org/10.3390/cleantechnol2040024).
- [18] Relvas, H., Lopes, D., & Armengol, J.M. (2025). Empowering communities: Advancements in air quality monitoring and citizen engagement. *Urban Climate*, 60, article number 102344. doi: [10.1016/j.uclim.2025.102344](https://doi.org/10.1016/j.uclim.2025.102344).
- [19] Robaina, M., Madaleno, M., Silva, S., Eusébio, C., Carneiro, M.J., Gama, C., Oliveira, K., Russo, M.A., & Monteiro, A. (2020). The relationship between tourism and air quality in five European countries. *Economic Analysis and Policy*, 67, 261-272. doi: [10.1016/j.eap.2020.07.012](https://doi.org/10.1016/j.eap.2020.07.012).
- [20] Song, N., & Zhang, Y. (2025). Exploring the relationship between tourism development and environmental pollution using an LSTM-based time series model. *Frontiers in Environmental Science*, 13, article number 1576039. doi: [10.3389/fenvs.2025.1576039](https://doi.org/10.3389/fenvs.2025.1576039).
- [21] Tan, Y., Yang, L., Liu, Y., Hu, S., Xu, K., & Liu, J. (2022). How does air quality affect tourist travel volume and destination preference? An analysis based on mobile tracking data. *Current Issues in Tourism*, 26(16), 2629-2646. doi: [10.1080/13683500.2022.2091430](https://doi.org/10.1080/13683500.2022.2091430).
- [22] Tobias, A., Carnerero, C., Reche, C., Massagué, J., Via, M., Minguillón, M.C., Alastuey, A., & Querol, X. (2020). Changes in air quality during the lockdown in Barcelona (Spain) one month into the SARS-CoV-2 epidemic. *Science of the Total Environment*, 726, article number 138540. doi: [10.1016/j.scitotenv.2020.138540](https://doi.org/10.1016/j.scitotenv.2020.138540).
- [23] Verkhovna Rada of Ukraine. (2014). *Association Agreement between Ukraine, of the one part, and the European Union, the European Atomic Energy Community and their Member States, of the other part*. Retrieved from https://zakon.rada.gov.ua/laws/show/984_011#Text.
- [24] Law of Ukraine No. 2697-VIII "On the Basic Principles (Strategy) of the State Environmental Policy of Ukraine for the Period up to 2030". (2019, February). Retrieved from <https://zakon.rada.gov.ua/laws/show/2697-19#Text>.
- [25] Wang, S., Song, R., Xu, Z., Chen, M., Di Tanna, G.L., Downey, L., Jan, S., & Si, L. (2024). The costs, health and economic impact of air pollution control strategies: A systematic review. *Global Health Research and Policy*, 9(1), article number 30. doi: [10.1186/s41256-024-00373-y](https://doi.org/10.1186/s41256-024-00373-y).
- [26] Wang, Y., Zang, S., Qiang, H., & Wang, J. (2023). Air pollution disclosing and tourism: Who are winners? *Annals of Tourism Research*, 103, article number 103659. doi: [10.1016/j.annals.2023.103659](https://doi.org/10.1016/j.annals.2023.103659).

- [27] World Health Organization. (2021). *WHO global air quality guidelines: Particulate matter (PM_{2.5} and PM₁₀), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide*. Retrieved from <https://surl.li/peaewe>.
- [28] Wu, X., Nethery, R.C., Sabath, B.M., Braun, D., & dominant, F. (2020). Air pollution and COVID-19 mortality in the United States: Strengths and limitations of an ecological regression analysis. *Science Advances*, 6(45), article number eabd4049. doi: 10.1126/sciadv.abd4049.
- [29] Yang, Y., Zhang, X., & Fu, Y. (2022). Foreign tourists' experiences under air pollution: Evidence from big data. *Tourism Management*, 88, article number 104423. doi: 10.1016/j.tourman.2021.104423.
- [30] World's Air Pollution. (n.d.). Retrieved from <https://waqi.info/>.

Формування регіональної системи екологічного моніторингу атмосферного повітря в туристичних дестинаціях

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Анотація. Незважаючи на розвиток систем екологічного моніторингу в Україні, існуючі підходи не враховують специфіку туристичних регіонів, що створює значні виклики для оцінки екологічних ризиків та забезпечення якості атмосферного повітря в умовах інтенсивних туристичних потоків. Метою дослідження було обґрунтування концепції формування регіональної системи моніторингу та управління екологічною безпекою туризму в територіальних громадах Івано-Франківської області з урахуванням європейських стандартів контролю якості атмосферного повітря. Методологічну основу становили аналіз європейського та національного екологічного законодавства, геопросторове моделювання на базі відкритих даних OpenStreetMap, індикаторів туристичної місткості та інтенсивності ночівель, а також оптимізаційні постановки задачі максимального покриття та р-медіани. Показано, що наявна державна система спостережень має обмежене просторове покриття, зорієнтована переважно на промислові центри, не охоплює курортні та гірські дестинації й не відображає пікові сезонні навантаження, пов'язані з туристичними потоками. Розроблено дворівневу архітектуру мережі, що поєднує три референсні станції високої точності (міський, долининний та промисловий фон) з адаптивною кількістю низьковартісних сенсорів (10-15 LCS), розташованих у ядрах туристичного попиту й транспортних коридорах. Зважена кластеризація 3 725 туристичних об'єктів виявила домінуючу роль курортної долини Поляниця-Яремча та дала змогу виділити конфігурацію з 12 сенсорів як збалансований варіант, що мінімізує середню відстань до пунктів моніторингу та забезпечує резервування вимірювань у чутливих зонах. Отримані результати створюють підґрунтя для поетапного розгортання мережі моніторингу якості повітря, інтеграції екологічних показників у політику управління туризмом, екологічний маркетинг територій та ESG-звітність суб'єктів туристичного бізнесу

Ключові слова: екологічна безпека туризму; якість атмосферного повітря; регіональна система моніторингу; низьковартісні сенсори; геопросторове моделювання; оптимізація розміщення станцій; туристичні дестинації