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Atmospheric Ecology Modeling for the Sustainable Development of the Urban Environment

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Abstract: The article considers the actual problem of the ecology of urban areas associated with air pollution by industrial and energy enterprises. The study is aimed at substantiating the method of forming a plan for atmospheric air pollution observation using mobile laboratories. The quantitative characteristic of sites for different urban development zones is determined as a set of estimates. The air pollution index was chosen as a total sanitary and hygienic criterion for assessing pollution. The implementation of the decision-making problem using the analytic network process method is considered. Parameters of the city and environment that affect the assessment of atmospheric air quality were selected in the course of the study. A network structure of mutual influence of the studied parameters is formed. The architecture of the decision support system based on the proposed method is given. The created software makes it possible to automate the modeling of the distribution of pollutants in the atmosphere. The computational experiment is presented on the example of the Volgograd agglomeration, Russia. The proposed approach can significantly improve the organization of monitoring by mobile laboratories and reduce the cost of obtaining data on urban air pollution without increasing the number of existing observation laboratories, both stationary and mobile.

Keywords: air quality; urban environment; pollution modeling; pollutants; population density; decision support; network analysis method; environmental monitoring; pollution concentration map; mobile survey organization plan

Citation: Rashevskiy, N.; Sadovnikova, N.; Ereshchenko, T.; Parygin, D.; Ignatyev, A. Atmospheric Ecology Modeling for the Sustainable Development of the Urban Environment. *Energies* **2023**, *16*, 1766. https://doi.org/10.3390/en16041766

Academic Editors: Alla Kravets, Valery Meshaklin, Petros Groumpos and Chirag Bhimani

Received: 11 December 2022
Revised: 4 February 2023
Accepted: 5 February 2023
Published: 10 February 2023

1. Introduction

At all times, cities have been centers of production and consumption of resources and power. New cities were created around large industrial enterprises. Urbanized territories are filled with industries of various sizes. Now, cities continue to consume huge amounts of energy, despite the transition to a knowledge economy and green technologies. Enterprises that generate energy, various energy consumers, as well as enterprises that extract and process natural resources for energy, are united in a fuel and energy complex, one of the results of which is a negative impact on the biosphere [1–3]. The impact of energy on the biosphere is manifested at all stages of energy production: in the extraction and transportation of resources, and in the production, transmission, and consumption of energy [4–6].

More than 70% of all emissions of pollutants into the atmosphere come from the energy sector (including electricity, heat, and transport) [7]. A huge share of electricity is generated at thermal power plants operating on solid fuels [8]. The air is polluted with sulfurous and sulfuric anhydrides, fluorides, and toxic impurities of arsenic and silicon dioxide when coal is burned [9]. All these integral components of modern urban infrastructure remain sources of environmental pollution [10]. Approaches to the formation of sustainable development of the human environment require the improvement of solutions in the field of preventing and reducing the impact of negative factors and conditions for the development of global warming [11–14].

The urban population continues to grow throughout the world and needs not only the benefits of civilization but also health [15]. Many studies have shown the relationship between the state of the population's health and atmospheric air quality [16–18]. At the same time, urbanization is always accompanied by environmental problems, which in turn affect the quality of life by changing the environment [19–25].

Air quality control is an important task to prevent climate change [26,27]. This requires improving approaches to building air quality monitoring systems [28]. The hardware and technologies used in the creation of stationary and mobile environmental monitoring laboratories are being modernized [29,30]. Approaches in the field of collecting and analyzing big data are used in the development of the software necessary for monitoring [31,32].

However, existing practices for monitoring the state of the urban environment often imply operational management. The environmental engineer selects a measurement location from a set that is often predetermined for a long period of time. This approach includes the use of a mobile laboratory, carried out at the request of residents. The choice of a point for measurement is carried out on the basis of an analysis of the averaged data of the previous period [33].

Mobile environmental laboratories are specialized equipment for conducting atmospheric air research on the content of harmful substances, as well as collecting meteorological data, installed on a motor vehicle. Such laboratories can analyze the situation directly at the alleged source of release after receiving complaints from organizations or citizens. Laboratories of this type can perform analysis of substances, similar to what is completed in stationary laboratories. There are two types of mobile laboratories:

- Route laboratories—perform measurements on the territory of the city by decision of the controlling organization;
- Mobile (under-flame) laboratories—perform measurements near and on the territory of sanitary zones of enterprises.

Modern trends involve the use of predictive analysis in all areas of human life [34,35]. Environmental protection is no exception. It is possible to implement pollution prediction for the entire study area. There are a number of studies that predict pollution from certain categories of pollution sources [36,37]. Thus, a direct selection of the object of measurement can be made from a set of terrain selected by the decision support system based on the purpose of the measurement (preferences of the decision maker) immediately before sending the mobile laboratory. This approach will make it possible to proceed to the implementation of the principles of smart sustainable development of the environment.

Several main types of air pollution sources in urban areas can be distinguished. These include linear, point, areal, and natural sources that affect the current state of the environment. Roads and streets with active car traffic are significant linear sources of air pollution [38,39]. About 280 components are found in exhaust gases, many of which are toxic and have an impact on human health. These are gaseous compounds such as nitric oxide and nitrogen dioxide, carbon monoxide, hydrocarbons such as olefins, benzopyrene, paraffins, aldehydes (formaldehyde, acrolein, acetaldehydes), solid compounds (lead, soot) and sulfur oxides [40,41].

The main factors of pollution from vehicles are [42,43]:

- Constant increase in traffic flows of both cars and trucks, transit road transport, especially in the warm season, throughout the entire length of the city territory;
- Steady increase in vehicles for personal use;
- Penetration of vehicles into residential areas;
- Multi-component emissions and difficult dispersion within the city.

Point sources of air pollution can be mobile and stationary (fixed). Point stationary sources are pipes of heating boilers, exhaust shafts, ventilation pipes of technological installations, deflectors, and chimneys of thermal power plants. Mobile sources of pollution are the exhaust pipes of diesel locomotives, motor ships, aircraft, vehicles, and other moving devices [44].

Area sources of pollution are undeveloped areas, such as demolition sites, new construction sites, and areas of unloading and loading operations [45]. They are scattered throughout the city, located near residential areas, and are sources of man-made dust, often occupy large areas, and can exist for a long time. New buildings under construction have a similar impact, especially point buildings located inside already inhabited areas [46].

Natural sources themselves can have a negative impact on the ecology of human life in the city, as well as enhance the influence of all the sources listed above [47,48].

The construction of models and the establishment of mathematical dependences of the spread of harmful impurities from sources such as vehicles and natural sources have not been studied enough [49]. Similar models are built on the basis of computational fluid dynamics equations [50,51]:

- The equation of state;
- The energy conservation equation;
- The momentum conservation equation;
- The continuity equation.

These equations represent the basic flow model, which, depending on the specifics of the problem being solved, can be supplemented with equations for models of turbulence, substance transfer, and chemical reactions, taking into account multiphaseness, electromagnetic interactions, etc. All the above mathematical formulations are a system of non-linear differential equations of the second order, which have an analytical solution only in very simple cases. The problem for a wide range of natural and technological processes can be solved numerically if the derivatives in the equations are replaced by finite differences created over small spatial and temporal intervals. The so-called discretization of space and time is carried out in the case of modeling a real process. The geometry of the process is divided into calculated cells, selected in a special way, and the processing time is divided into calculated time intervals [52,53].

Modeling of pollution processes based on atmospheric monitoring makes it possible to accurately solve the following problems [54,55]:

- Placement of environmental monitoring laboratories;
- Assessment of the contribution of individual industrial facilities to the pollution of residential areas;
- Forecasting of unfavorable situations of emission distribution;
- Selection of a site for the construction of a specific infrastructure object (school, residential building, stadium, or industrial site);
- Development of plans for the evacuation of the population in case of salvo emissions;
- Etc.

All this can be solved in real time and promptly make management decisions using mathematical modeling methods as a means of studying processes and phenomena [56,57]. Mathematical models of atmospheric pollution can be the basis for the construction of automated environmental monitoring systems [58,59].

Technologies and methods of spatial statistics are increasingly used in modern scientific research [60,61]. This theory involves determining the dependence of the location of objects in space based on statistical data [62]. As the analysis showed, very little information on air pollution is collected in the municipalities of Russia [63], as a result of which one may encounter an "environmental error" (a formal error in the interpretation of statistical data) [64,65]. Statistical ecological fallacy includes: discrepancies between system-wide ecological correlations and partial correlations, Simpson's paradox, etc. [66,67].

A decision support system (DSS) is a system that helps individuals, using tools such as information gathering, modeling, and visualization, to make decisions in complex problems of the subject area [68,69]. It must be stable, responsive to user actions and conveniently configured. DSS provides an opportunity for decision-makers to analyze various alternatives to assist in the formation and adoption of decisions [70,71].

The use of decision support systems in ecology opens up an opportunity to improve air quality planning in large cities [72,73]. Decision support systems should include emission inventories, air quality monitoring, modeling, mapping, and air quality assessment for various management strategies [74,75].

Some examples of decision support systems used by local authorities in large European cities can be given. Swedish AirViro [76], Austrian AirWare [77], Norwegian AirQUIS [78], and Swedish EnviMan [79] are used in cities such as Stockholm, Lisbon, Milan, Berlin, Geneva, Vienna, Paris, Oslo, and Athens. Air quality DSSs such as Airviro, AirWare, AirQuis, and EnviMan have a low resolution that does not match the high spatial variability in urban environments.

Research in the field of DSS development for atmospheric air quality management has been carried out for a long time [80,81].

Sarah Alves et al. point out that only single pollutants and only inhalation exposure are currently considered by the US Environmental Protection Agency in environmental policy planning. Yet the combination of pollutants affects people in reality. Pollutants enter the body, including water, food, and through skin. The authors explore how the cumulative effect of pollutants can be considered at the legislative level [82].

Reza Eslamipoor and Abbas Sepehriar analyze the problem of moving enterprises to another territory, which is solved using SWOT analysis and the hierarchy analysis method [83].

Ainhoa González et al. understand urban metabolism as the interaction of energy and substances on a city scale and propose to calculate such flows and use them in decision-making [84].

Giorgio Guariso et al. point out that meeting the recent European Union environmental requirements can be very costly. The authors propose a methodology for solving this problem [85].

Weeberb João Requia et al. used geographic information systems, hierarchy analysis method, and fuzzy logic to calculate the effectiveness of pollution abatement measures. The most effective measures were the development of public transport and traffic control [86].

Gregory Rowangould proposes to attract investments in private railway companies in order to reduce freight traffic and, consequently, air pollution. The author explores the factors that complicate the decision to allocate funds [33].

Wei-Che Hsu et al. describe a DSS for assessing ground-level ozone control strategies [87].

Christos Vlachokostas et al. point out that decision-making on pollution abatement strategies is a long and costly process and propose DSS to preliminarily narrow down the set of alternative measures to a small number that can already be considered without DSS [88].

The purpose of this study is to implement a method for planning atmospheric air observations using mobile laboratories. Such a method should allow for obtaining all the necessary information from mobile laboratories, including indicators of pollution by various substances. At the same time, the data obtained from the system for modeling the spread of pollutants should be used in organizing the work of mobile laboratories. It is assumed that this will allow obtaining more initial information about the area for making management decisions and increasing the level of automation of business processes.

2. Methodology

Environmental decision-making systems require a large amount of input data in the form of urban maps of pollution concentrations. This is especially important when assessing the quality of atmospheric air.

These data are obtained from ecological observation laboratories when there are enough of them for the necessary studies, or by means of modeling systems when information is not enough. Methods of mathematical modeling must be applied to create a DSS for assessing the quality of atmospheric air for a large city at the modern level. So, for example, there are only 6 automated environmental monitoring laboratories and one mobile laboratory in Volgograd, which is not enough for a city with an area of 859.4 km^2. A similar situation exists in other cities in Russia. Modern management decision support systems cannot be used on an insufficient amount of information. Therefore, it is important to use the pollutant dispersion modeling system for municipalities and regions as a whole. It will also allow more efficient use of mobile air monitoring laboratories.

The observation organization plan formation method is proposed to be implemented according to the developed procedure (Figure 1). The developed method includes the following steps:

1. "Terrain data preparation". Data on terrain, types of land use, etc., must be obtained at this stage for the study area. These data for a particular territory are obtained once.
2. "Preparation of data on pollution sources". An environmental engineer collects data on the parameters of pollution sources and forms an archive based on them. The information obtained is used in forecasting the concentrations of atmospheric air pollutants by the pollutant distribution modeling system.
3. "Formation of measurement goals". The determination of the purpose of the measurements by the mobile laboratory is carried out by the decision maker. The purpose of the measurement is determined based on current preferences.
4. "DSS setup". The decision maker adjusts the DSS based on the purpose of the measurements.
5. "Formation of predicted maps of pollutant concentrations". Dynamic data are being prepared. Such data include: meteorological data on air temperature, humidity, pressure, wind speed and direction at different heights, etc.
6. "Formation of a set of measurement sites". The decision support system is run. The assessment of individual sections of the territory is based on maps of predicted concentrations of pollutants and user preferences. A list of ten terrain sites is formed as a result. The list is ranked according to the need to send a mobile laboratory, depending on the purpose of the measurements.

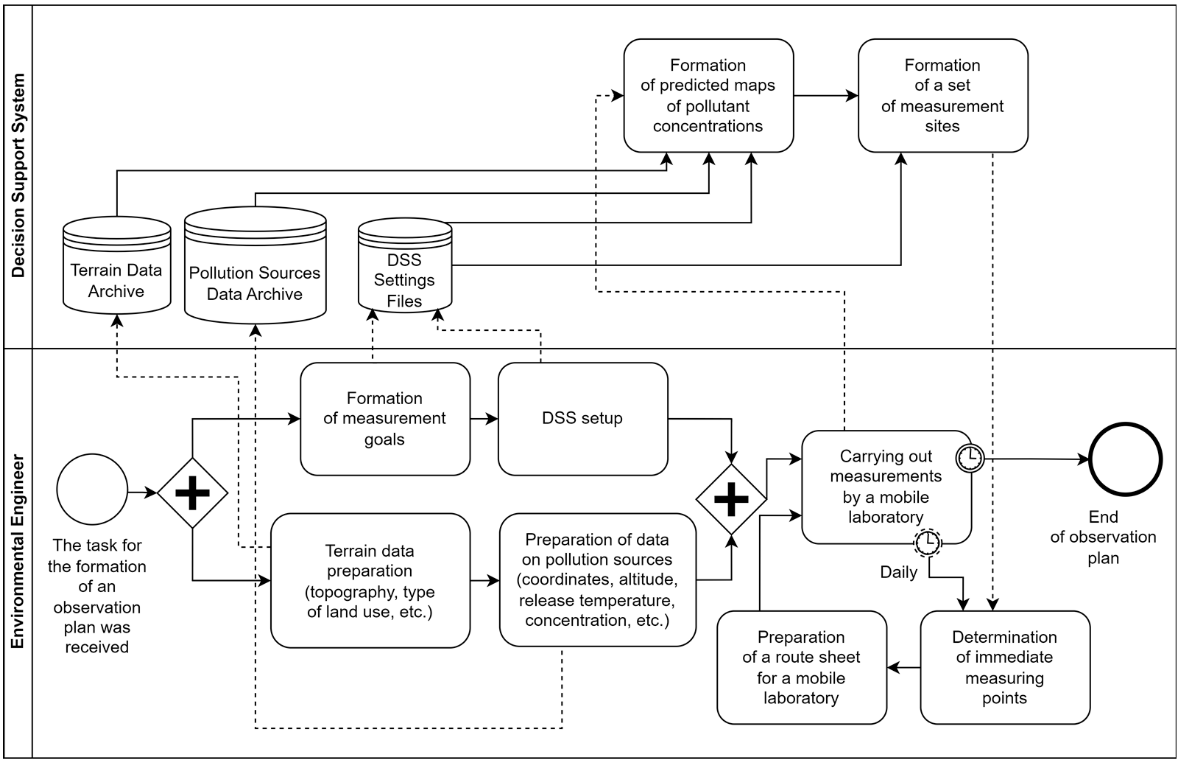


Figure 1. Observation plan formation method.

So, the formation of an observation organization plan requires the following actions. The analyzed urban area is represented as a two-dimensional matrix, the elements of which correspond to a local area of the territory. The size of the area corresponding to one element of 500 by 500 m was chosen on the basis of a study carried out in [89]. This size is the most optimal for modeling, as it reduces the number of areas with very close values and leaves the possibility of physical access of the laboratory to this area for detailed study.

The elements of this matrix include information about the area (alternatives). This information will determine the need to search for a contaminated site for measurements by mobile laboratories. Indexes (i, j) define each cell of the matrix. The most preferred solutions form a subset X (a subset of feasible values) of the solution space W. The subset X intersects W. The set R bounds the solution space. Restrictions are associated with certain properties of the territory, which are due to the influence of the following factors:

- Anthropogenic—this restriction implies the presence of secret objects, closed objects, etc.;
- Natural—it can be swamps, lakes, and other inaccessible areas of the terrain;
- Social—they are related to the preferences of residents or decision-makers.

$R = [R_1 \ldots R_q]$, where q is the number of restrictions imposed on the initial sections of the territory, which are evaluated according to four criteria:

$$K = \{K_1, K_2, K_3, K_4\}, \quad (1)$$

where K_1—atmospheric pollution; K_2—territory characteristics; K_3—cost-effectiveness of measurements; K_4—measurements history.

Y is a set of weights of individual sections calculated on the basis of available information. Quantitative characteristics of plots are defined as a set of estimates

$$P \times T \times E \times H \to Y \quad (2)$$

where P—assessment according to the criterion "Atmospheric Pollution";

T—assessment according to the criterion "Territory Characteristics";

E—assessment according to the criterion "Cost-Effectiveness of Measurements";

H—assessment according to the criterion "Measurements History".

Significance (rank) of a separate area is calculated as a linear combination of single indicators

$$Y^{ij} = P^{ij}\alpha_1 + T^{ij}\alpha_2 + E^{ij}\alpha_3 + H^{ij}\alpha_4 \quad (3)$$

The rank of each site on the ground is represented as a linear combination of single indicators, i.e., in the form of the sum of multiplications of each normalized value of partial criteria and numerical coefficients of the weight of the criteria: α_1, α_2, α_3, α_4.

The criteria of "Cost-Effectiveness of Measurements", "Measurements History", and "Territory Characteristics" are static and change extremely rarely.

Criterion "Atmospheric Pollution" K_1 is dynamic. It is calculated separately for each period of time, where the mutual influence of various pollutants at a certain moment is determined. The integrated air quality index is used to analyze air pollution in an urban area.

Many different indicators of air quality are used around the world. Canada Air Quality Health Index (AQHI) is one of the most well-known [90]. This index has been used in Canada since 2005. AQHI is a number from 1 to 10 (or higher) that indicates how much health risk arises from local air pollution. The value of the indicator can exceed 10 in rare cases when the pollution is especially high. The AQHI value scale is divided into intervals, which correspond to the designation of the health risk:

1. From 1 to 3—low risk;
2. From 4 to 6—medium risk;
3. From 7 to 10—high risk;
4. More than 10—very high risk.

AQHI distinguishes two categories of citizens: (i) those sensitive to pollution (at-risk population), including people with respiratory and cardiovascular diseases, children, and the elderly, and (ii) ordinary citizens (general population). The AQHI indicator makes separate recommendations for each category of citizens and for each level of pollution.

"Territory Characteristics" is a criterion that is evaluated by five components and is a combination of them:

$$K_2 = \{T_1, T_2, T_3, T_4, T_5\}. \quad (4)$$

Sub-criterion T_1 is "Urban planning zone". This criterion determines the zone established by the town planning regulations of the Town Planning Code of the Russian Federation. The resource of the Cartographic Fund contains maps of urban zoning [91]. The decision maker selects the territory of the highest priority at the moment for measurements by mobile environmental laboratories. The choice is determined depending on the need for measurements in certain areas due to possible harmful emissions. These may be areas:

- Public and business, such as educational institutions, healthcare facilities, kindergartens, and trade and commercial enterprises;
- Residential;
- Recreational, tourist, park areas, and beaches;
- Agricultural;
- Industrial;
- Restricted areas and military facilities;
- Special areas such as municipal waste dumps.

Sub-criterion T_2 is "Number of social objects". It determines the number of public, state and municipal institutions at the proposed site of contamination.

Sub-criterion T_3 is "The number of open areas for recreation and sports located in disadvantaged areas of the urban area". It is unsafe for weakened people, even with small air pollution, on the verge of permissible, to be outdoors and play sports [90]. Special websites publish all information about the location of public and commercial institutions, various outdoor events, and sports competitions [92].

Sub-criterion T_4 is "The number of complaints received from the population of the city". This sub-criterion determines the probability of atmospheric air pollution in a certain area on the basis of complaints from the population to various administrative, state, and independent organizations.

Sub-criterion T_5 is "Reconstruction area". Areas of industrial or civil construction are investigated for the possible impact of air pollution from industrial plants, landfills, and other sources. This is relevant when various industrial enterprises are being reconstructed and closed, and residential and commercial buildings, new highways, and other structures are being built on their territory. Data on reconstruction and new construction are posted on the information resource of the Cartographic Fund [91].

Data for sub-criteria that are quantified are taken from open sources. These values are normalized to 1.

Sub-criteria that have a qualitative value are compared by the decision maker using the analytic hierarchy process method based on the task at hand. The result of this is also values normalized to 1.

The criterion "Territory Characteristics" (T^{ij}) is additive and evaluates the territory (i, j) for each of its sub-criteria:

$$T^{ij} = \sum_{k=1}^{5} \alpha_k^T x_{ij}^{T_k} \quad (5)$$

where α_k^T is the weight of the k-th sub-criterion, and $x_{ij}^{T_k}$ is the assessment of the alternative by the sub-criterion.

The criterion "Cost-Effectiveness of Measurements" K_3 is evaluated according to two sub-criteria:

$$K_3 = \{E_1, E_2\}. \quad (6)$$

Sub-criterion E_1 is the cost of sending a mobile laboratory for measurements. It includes the cost of operating a mobile laboratory when taking measurements in a certain area. Sub-criterion is calculated according to the standards of car operation.

Sub-criterion E_2 is the time spent on logistics and measurements by the mobile laboratory.

The criterion "Cost-Effectiveness of Measurements" (E^{ij}) is calculated as the sum of multiplying the assessment of the alternative by its weight:

$$E^{ij} = \sum_{z=1}^{2} \alpha_z^E x_{ij}^{E_z} \tag{7}$$

where α_z^E is the weight of the z-th sub-criterion of the component, and $x_{ij}^{E_z}$ is the assessment of the alternative by the sub-criterion E_z.

The criterion "Measurements History" K_4 is evaluated according to two sub-criteria:

$$K_4 = \{H_1, H_2\}. \tag{8}$$

Sub-criterion H_1 is the number of trips of a mobile laboratory to the same measurement area.

Sub-criterion H_2 is the number of recorded exceedances of the maximum permissible concentrations (MPC) during measurements by a mobile laboratory in the same area for the entire period of measurements.

The archive used to evaluate data according to this criterion is formed on the basis of registration of departures and measurement results.

3. Results and Discussion

3.1. Implementation of the Decision-Making Problem Using the Analytic Network Process

The analytic network process method developed by the mathematician T. Saaty [93] is proposed to be used to solve the problem. This approach extends the possibilities of the analytic hierarchy process method and allows solving problems with a complex formulation and opposite relationships by introducing network structures and taking into account different preferences.

It is important to take into account the opinion of interested people when solving the problem of forming a plan for organizing atmospheric air observations with a specific task using mobile laboratories. For example, the Ecology Committee conducts measurements to identify the most dangerous areas of the territory throughout the city [94]. The City Administration needs to take measurements of the area where there is a cluster of state and municipal institutions. The Health and Sports Committee makes a request for a study of outdoor sports fields and weekend recreation areas. Therefore, it is necessary to take into account the factors influencing the solution of the task, depending on the situation.

The interrelation of the system components, which affects the formation of the assessment of the study site for atmospheric air pollution in the urban area, is displayed in the component diagram (Figure 2). The arrows show the influence of some sub-criteria on others. If the arrow is unidirectional, then the relationship is one-way. If the arrow is double, then there is a relationship between sub-criteria.

The diagram shows the dependence of the choice of an alternative on the components "Atmospheric Pollution", "Territory Characteristics", "Cost-Effectiveness of Measurements", and "Measurements History", which determine and limit the construction of a plan for the departure of mobile laboratory. The "Measurements History" component depends on the "Atmospheric Pollution" criterion and is interdependent with the "Territory Characteristics" component. Interdependence is determined by the possibility of changing the structure of the urban territory, which must necessarily be reflected in the archive base.

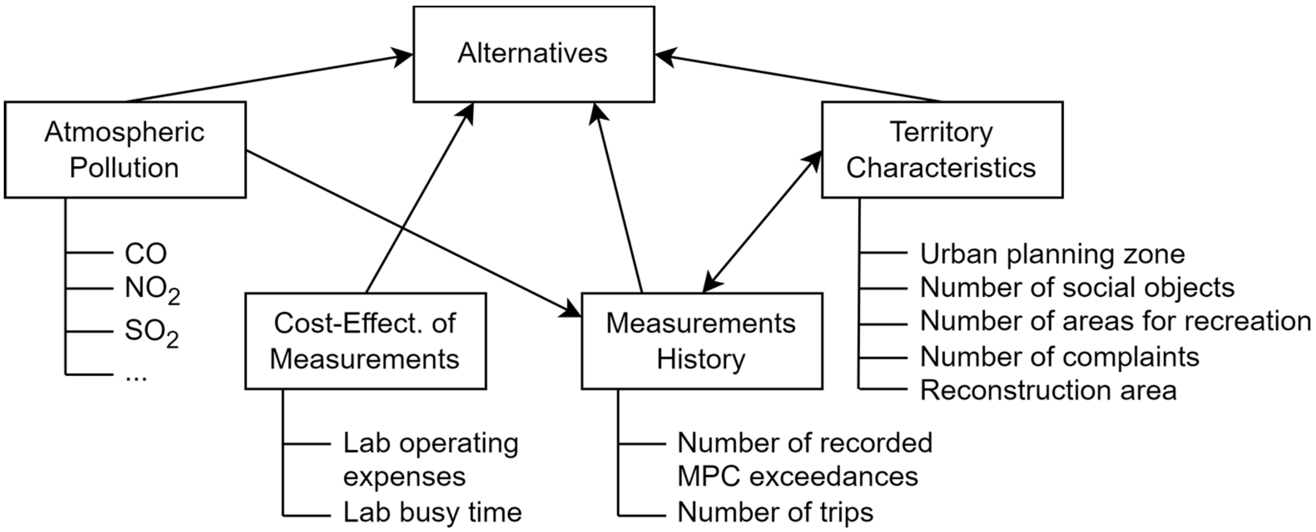


Figure 2. Diagram of system components (where CO—carbon monoxide; NO_2—nitrogen dioxide; SO_2—sulfur dioxide).

It should immediately be noted that the population is actually one of the most important aspects of this system. Yet directly, "population" is absent as a separate criterion or sub-criterion, since the types of influence of atmospheric air pollution on people were just identified as criteria. For example, the "Atmospheric Pollution" criterion evaluates harm to a person's physical health. "Territory Characteristics" takes into account social aspects: how many people live in a particular area (urban planning zone), how many children can be in the study area (social facilities, including schools, and kindergartens), etc.

Figure 3 shows the relationship of the elements of the components in the form of a matrix, which reflects the influence of the criteria of the components within the system. For example, all elements of the "Territory Characteristics" component are associated with the element "Number of social objects", since the decision maker can set the goal of air pollution measurements, where the presence of social objects in any component characterizing the urban area will be important. There are similar links between the elements of the "Territory Characteristics" component and the elements of "Number of areas for recreation" and "Urban planning zone". Yet only the elements of the "Territory Characteristics" component affect the "Measurements History" component. The "Alternatives" component consists of a set of elements that represent the studied areas of the city. They are evaluated on all elements of the components.

This matrix shows the influence or mutual influence of some sub-criteria on others. Therefore, some qualitative parameters influence themselves. For example, the type of building may be industrial areas or residential buildings. Choosing one or the other option (weight) can change the ranking result.

Pollutants are quantities that cannot be directly related to themselves but can be related to other pollutants. This makes it possible to use different indices for assessing air quality (AQI, AQHI, etc.), since the contribution of pollutants to atmospheric air pollution differs in different methods. It also makes it possible to take into account the transformation of some chemicals into others, or the lack of control in the region over one or another substance.

Relationships between sub-criteria were identified by expert analysis. Representatives of public organizations, municipalities, and state bodies in the field of environmental protection acted as experts.

		Alternatives			Territory Characteristics					Cost-Effect.		Meas. History		Atmospheric Pollution				
		Alternative 1	...	Alternative N	Urban planning zone	Number of social objects	Num. of recreation areas	Number of complaints	Reconstruction area	Lab operating expenses	Lab busy time	Number of trips	Number MPC exceed.	SO_2	CO	PM10	NO_2	Pollutant M
Alternatives	Alternative 1				x	x	x	x	x	x	x	x	x	x	x	x	x	x
	...				x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Alternative N				x	x	x	x	x	x	x	x	x	x	x	x	x	x
Territory Characteristics	Urban planning zone				x	x	x	x	x			x	x					
	Number of social objects				x		x	x					x					
	Num. of recreation areas				x	x		x					x					
	Number of complaints				x	x	x		x			x	x					
	Reconstruction area				x	x	x						x					
Cost-Effect.	Lab operating expenses																	
	Lab busy time																	
Meas. History	Number of trips					x	x		x									
	Number MPC exceed.					x	x		x									
Atmospheric Pollution	SO_2														x	x	x	x
	CO													x		x	x	x
	PM10													x	x		x	x
	NO_2													x	x	x		x
	Pollutant M													x	x	x	x	

Figure 3. Matrix of mutual influence of criteria components (PM10—particles of a substance with a diameter of 10 µm or less; the symbol "×" means the presence of a relationship).

3.2. Development of the Architecture of the Software Complex for the Formation of a Plan for Observing the Atmospheric Air of the City

A software package for automating the run of modeling systems and performing calculations for a decision support system was developed on the basis of the proposed methods [95,96]. The application was developed in the form of independent software modules that can work both separately and as part of a single software package.

This approach allows for gradually refining the system by adding new functionality or improving existing modules. The independence of the modules will also allow the use of other systems for modeling the spread of pollutants or decision-making methods [97].

The programming languages Python 3.6 and C++ were used to implement the software modules. These programming languages will allow further development of the system, where modules for intelligent decision support in the field of atmospheric air quality will be implemented [98].

There are three main components of the software package:

- Package of modules for automating the simulation of the distribution of pollutants in the atmosphere (Figure 4);
- Package that implements a decision support system (Figure 5);
- Package of modules for visualization of simulation results (Figure 6).

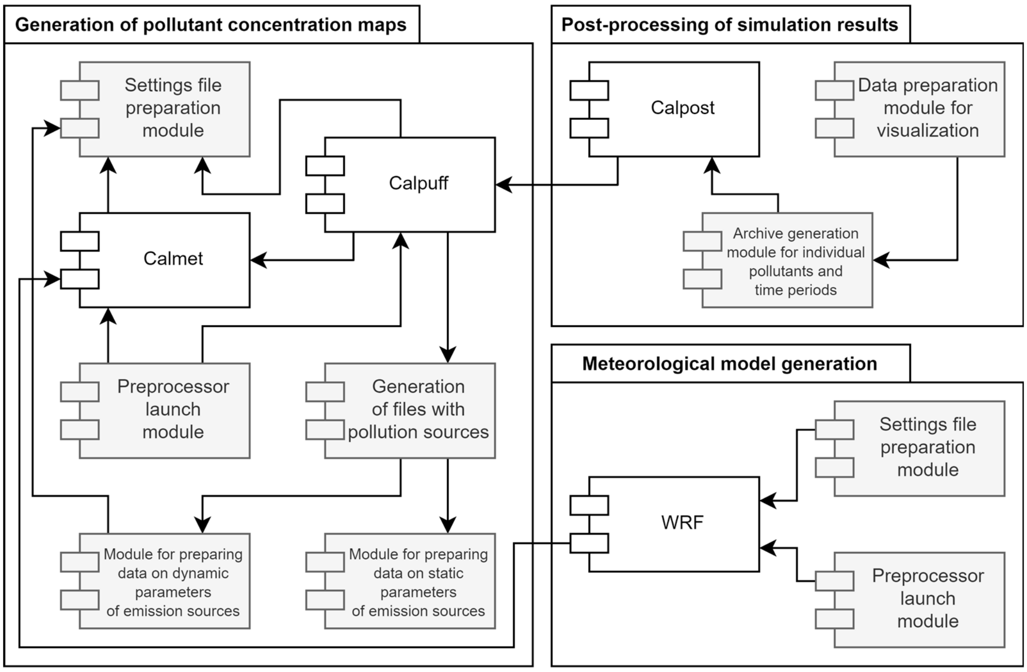


Figure 4. UML diagram of the components of the package "Automation of modeling the distribution of pollutants in the atmosphere" (modules that were developed during the study are highlighted in gray here and below in Figures 5 and 6).

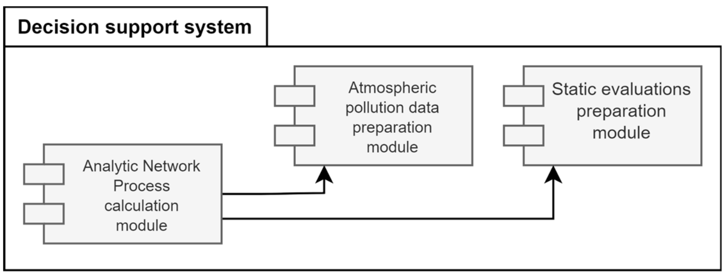


Figure 5. UML diagram of the components of the package "Decision support system".

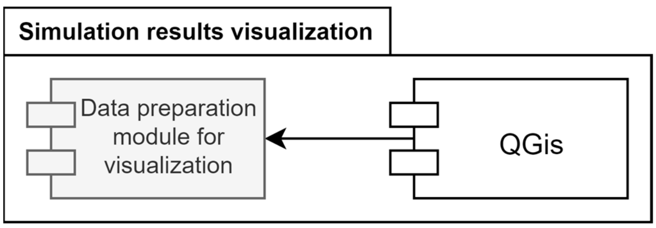


Figure 6. UML diagram of the components of the package "Simulation results visualization".

Features of the implementation of the preprocessors of the Weather Research and Forecasting (WRF) [99] and Calpuff [100] modeling systems do not allow fully automating their run. Moreover, modeling of a three-dimensional meteorological model in the WRF system must be carried out in an operating system based on OS Linux. Additionally, the simulation of the spread of pollutants in the Calpuff system is carried out in the Microsoft Windows operating system.

The developed simulation automation package includes the following modules:

- "Settings file preparation module". This module is implemented both in the package for generating a meteorological model and in the package for generating maps of pollutant concentrations. In the first case, WRF system parameter files are configured, and in the second, Calpuff. They have a similar workflow. They adjust the source files of the simulation system preprocessors for the specified geographic coordinates and simulation periods, as well as other general settings for all preprocessors;

- "Preprocessor run module". This software module is implemented in two packages and organizes the sequential run of modeling system preprocessors. It links the output of some modules to the inputs of others;
- "Module for preparing data on static parameters of emission sources". Processing of source text files with parameters of emission sources is implemented in this component. Emission source parameters are usually obtained in .xls or .csv format. Settings files (ptemarb.dat, lnemarb.dat, etc.), are generated with emission source parameters. The files contain information about source coordinates, height, and other constant data for the Calpuff modeling system. Only those lines of files formed in this module are responsible for static information;
- "Module for preparing data on dynamic parameters of emission sources". Processing and preparation of data for the formation of the dynamic part of files with source parameters are implemented in this program module. Emissions of pollutants in given simulation time periods are specified, as well as the release rate and temperature;
- "Generation of files with pollution sources". The module generates files with the parameters of emission sources based on the information prepared in the two previous modules;
- "Archive generation module for individual pollutants and time periods". Additional data post-processing is required after running the standard Calmet [101], Calpuff, and Calpost preprocessors. The Calpost preprocessor file is processed by this program module. Data with predicted concentrations of pollutants are divided into directories by individual pollutants and time periods. A separate text file with a pollution matrix corresponds to each hour;
- "Data preparation module for visualization". Coordinates for display on maps in geographic information systems are added to files with information on pollutant concentrations.

The "Decision support system" package (Figure 5) includes the following main components:

- "Atmospheric pollution data preparation module". This software module calculates the weights of individual terrain areas according to the "Atmospheric Pollution" criterion. The calculation is carried out according to a complex indicator of atmospheric air quality. Atmospheric pollution index is used in this study. However, the system allows us to add the implementation of the calculation using any international methodology;
- "Static evaluations preparation module". Preparation and processing of data for automatic calculation of estimates of alternatives according to the criteria "Territory Characteristics", "Cost-Effectiveness of Measurements" and "Measurements History" are implemented in the component. For example, text files containing information about the social objects of the region obtained from specialized resources are processed in this module;
- "Analytic Network Process calculation module". The component organizes the assessment of the importance of criteria and sub-criteria of the decision maker using a pairwise comparison. The final calculation of the weights of the studied areas and the ranking of alternatives are also implemented in this module.

The "Simulation results visualization" package (Figure 6) includes the following components:

- "Data preparation module for visualization". This module recalculates pollutant concentrations into MPC shares and other necessary air quality indicators.
- "QGis" [102]. A geographic information system in which the user loads information from maps of pollutant concentrations and customizes the display using polygons and other visual effects.

The implemented software package provides the user with the ability to select the run preprocessors of the Calpuff simulation system. This feature allows for reducing the time when simulating situations with identical conditions (Figure 7).

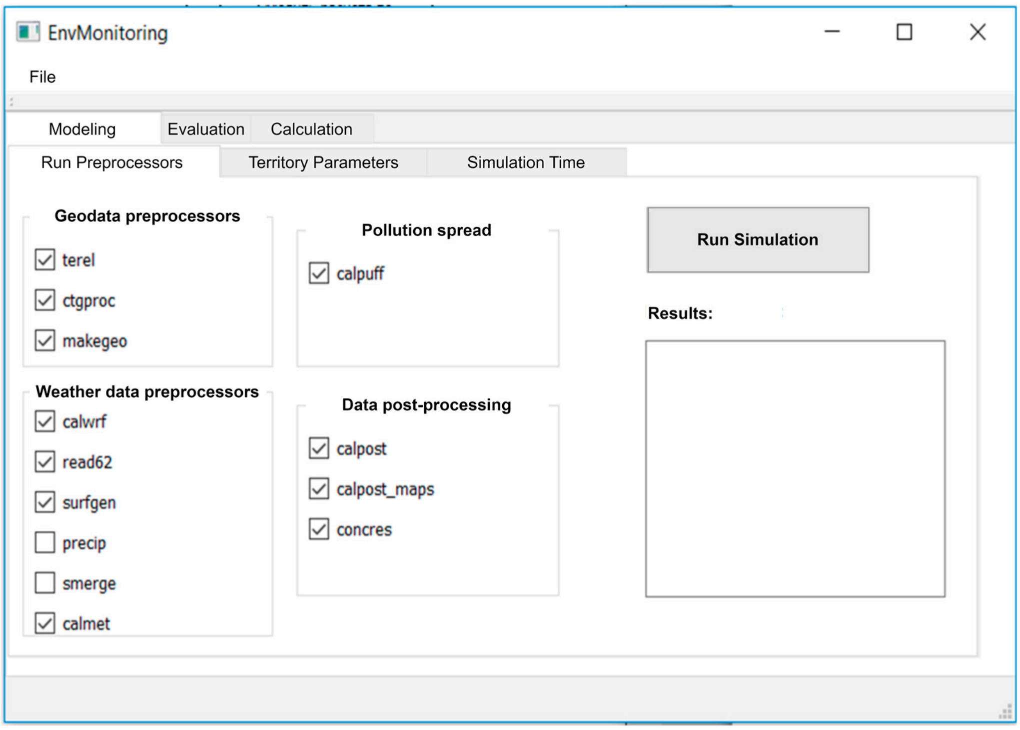


Figure 7. Screen for selecting modules of the software package to run.

The decision maker conducts a comparison of components and elements in the software package by pairwise comparison, where "9" shows the greatest preference, and "−9" is the least (Figure 8).

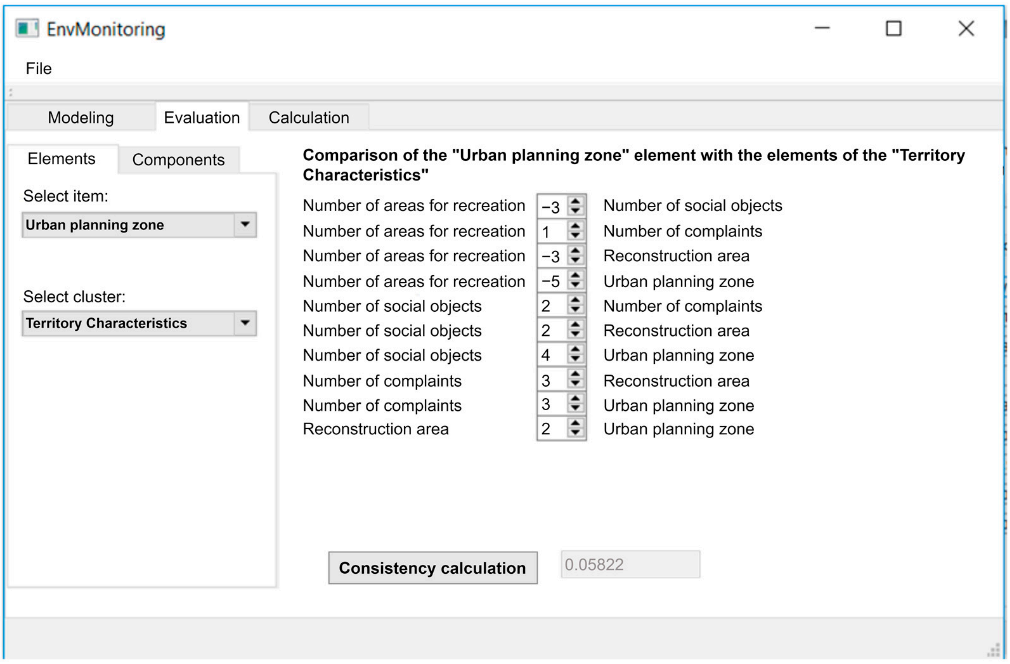


Figure 8. Screen for obtaining estimates of the relationship between components and elements of the system.

3.3. Modeling the Spread of Pollutants

Figure 9 shows the territory for which the computational experiment was carried out. The computational experiment was carried out for the cities of Volgograd and Volzhsky, Russia. One of the key stationary point sources of air pollution in the Volgograd agglomeration is Combined Heat and Power Plant 1 (CHPP-1) of Volzhsky, CHPP-2, and CHPP-3 Volgograd, Volgograd State District Power Plant [103]. The former Volgograd Tractor Plant is an example of an areal source, where industrial facilities are being demolished near a residential area. A similar situation occurs with other decommissioned enterprises of the city, such as the Volgograd Shipbuilding Plant, the Volgograd Steel Wire and Rope Plant, and the «Khimprom» Chemical Plant [104]. Moreover, location in a semi-desert zone, sharply continental climate, characterized by insufficient precipitation, strong winds, dry air, and hot summers, contribute to active dust formation in the entire territory of the Volgograd agglomeration [105,106].

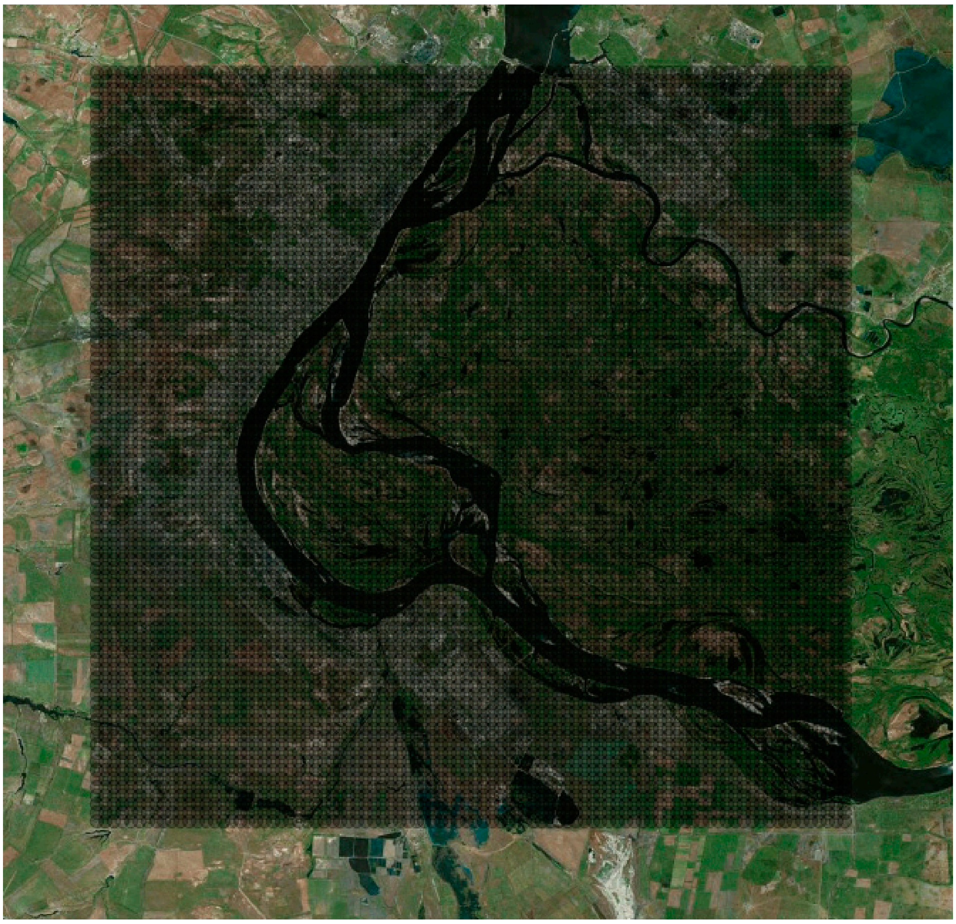


Figure 9. Territory of the computational experiment.

- The following terrain parameters are defined:
- Date and time: 01.06.2022, 07:00;
- Atmospheric air temperature: +12.3 °C;
- Atmosphere pressure: 748 mmHg;
- Air humidity: 77%;
- Wind direction and speed: northeast, 8 m/s;
- Precipitation: none;
- Cloudy: mostly cloudy (70%);
- Latitude and longitude of origin: 48.414373, 44.317071;
- Simulation cell size 500 × 500 m;

- Simulation matrix size 100 × 100 cells;
- Pollutants under investigation: SO_2, NO_2, CO, PM10.

Landscape and land use data were also obtained.

The following terrain data required for air pollution modeling were obtained according to the proposed method:

- Sources of pollutant emissions;
- Meteorological data;
- Landscape.

The relevant data were obtained for the operation of the decision support system module:

- Types of land use;
- Information about city buildings, etc.

Next, the modules for preparing the necessary data were run. Then, the experts (environmental engineers) completed the assessment, according to the goal (Figure 8). The ranked measurement sites were obtained as a result of the work of the implemented software package.

The goal of the simulation was formulated as follows: to find a place with the highest air pollution and the highest population density to send a mobile environmental monitoring laboratory.

Estimates of the elements and components of the system were obtained from experts. The relevant data are entered into the software package.

Pollutant concentration maps were obtained as a result of a computational experiment: NO_2 (Figure 10a); SO_2 (Figure 10b); CO (Figure 10c); PM10—there were no data on pollution sources for the study period, so modeling was not carried out for this pollutant.

(**a**) (**b**) (**c**)

Figure 10. Results of the computational experiment: (**a**) NO_2; (**b**) SO_2; (**c**) CO.

Flames from pollution sources containing NO_2 emissions in the city of Volzhsky are directed at the city itself and also extend to the Traktorozavodsky, Dzerzhinsky, and Krasnooktyabrsky districts of the city of Volgograd. Sources of pollution in the industrial area of the Sovetsky district of the city of Volgograd pollute the territory of this district only. Industrial enterprises of the Krasnoarmeisky district also pollute the residential area with insignificant concentrations.

Pollution from SO_2 is observed only in two zones from enterprises in the Volzhsky and Krasnoarmeisky districts of the city of Volgograd. Pollutant concentrations are low in the northern part of the simulation area. Increased pollution values are observed in the southern part, however, pollution clouds spread toward individual residential buildings, summer cottages, and non-residential areas. Pollution is either absent or low in densely populated areas.

CO pollution is absent in the southern districts. A small cloud with extremely low pollution values is formed in the central part of the city of Volgograd according to the data of a computational experiment.

The maximum permissible values outside the sanitary protection zones do not exceed the concentration of any of the simulated pollutants. Overlapping of multiple pollutants occurs in some areas of densely populated areas.

A total of 10,000 cells are obtained for further analysis of the possible departure of the mobile laboratory based on the conditions of simulation of the spread of pollutants. Three sites in different districts of the city of Volgograd are allocated for detailed consideration (Figure 11). Site 1 is a multi-story development (nine or more floors) with a complete absence of industrial enterprises. Site 2 is a mid-rise development (about five floors) with adjacent industrial plants. Site 3 is a low-rise development at a small distance from the industrial conglomeration.

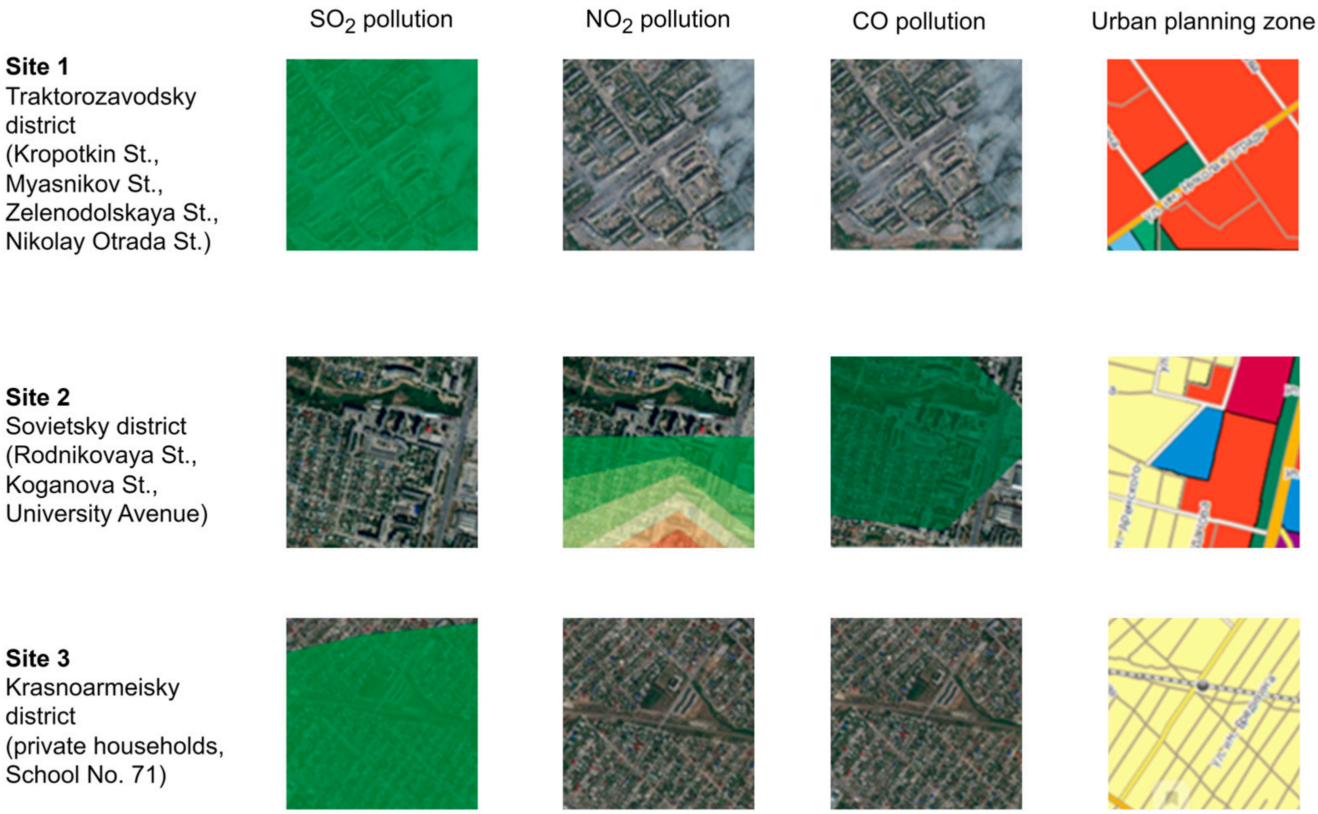
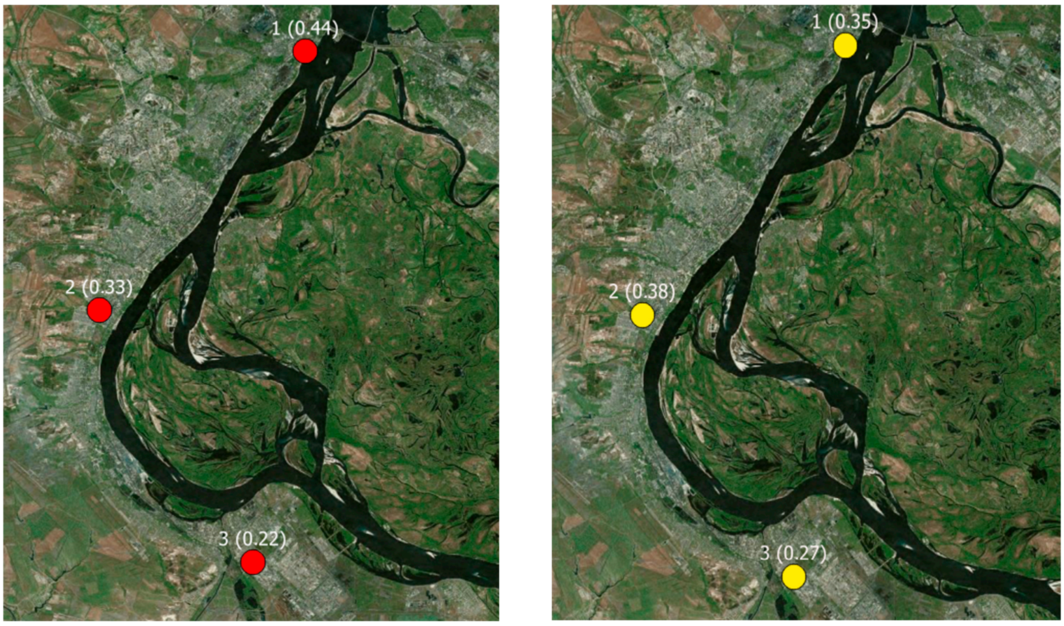


Figure 11. Sites for analysis of the work of the proposed approach.

Invited experts from a specialized environmental organization filled in the values of the estimates of the relationship of subcriteria based on the objectives of the measurements (Figure 8). Further, the estimates of the terrain sections are calculated by the software package using the analytic network process method based on the data obtained as a result of modeling, as well as static data. The results obtained are normalized to 1.

The display of calculations for the considered areas of the terrain is shown in brackets in Figure 12a. The sites were ranked as follows: the first place is site No. 1, the second is site No. 2, and the third is site No. 3.



(**a**) (**b**)

Figure 12. Displaying a fragment of ranked alternatives in the QGis geographic information system: (**a**) primary goal; (**b**) additional goal.

Further, the goal was changed to find a place with the highest air pollution to send a mobile environmental monitoring laboratory.

The order of preference for choosing sites for sending a mobile laboratory changed when a new goal was set (Figure 12b). Site 2 received the highest priority, site 1 was in second place, and site 3 was in last place, as in the first example. This rearrangement occurred because the first site has a higher population density, but fewer quantitative indicators of pollutant concentrations and the second one has a smaller population, but the concentration of pollutants is higher and pollution is with two pollutants (NO_2 and CO).

The software package formed a plan for conducting observations based on the calculations (Table 1).

Table 1. Fragment of the observation plan table.

Measurements Goal	Measuring Point Identifier on the Terrain Map	The Rank of a Terrain Piece, Normalized to One
Find a place with the highest air pollution and the highest population density to send a mobile environmental monitoring laboratory	1 2 3	0.44 0.33 0.23
Find a place with the highest air pollution to send a mobile environmental monitoring laboratory	2 1 3	0.38 0.35 0.27

The results obtained using the developed DSS and the existing "Method for calculating the dispersion of emissions of harmful (polluting) substances in the atmospheric air" (approved by order of the Ministry of Natural Resources of Russia dated 06.06.2017 No. 273) were compared with the actual data obtained as a result of measurements by a mobile laboratory. Table 2 shows a fragment of the results of experimental studies performed to test the proposed approach.

Table 2. Pollutant concentrations obtained from the experiment.

Date and Time	Coordinates (Latitude and Longitude)	Pollutant	Data Obtained Using Existing Methodology (mg/m^3)	Data Obtained Using the Proposed Method (mg/m^3)	Actual Values (mg/m^3)	The Error of the Existing Technique	Error of the Proposed Method
25 July 2022 11:00	48.81964, 44.63078	CO	1.985	1.779	1.47	0.5145	0.3087
		NO_2	0.081	0.069	0.059	0.02242	0.01003
		SO_2	0.050	0.043	0.034	0.01632	0.00884
26 July 2022 12:00		CO	1.106	0.909	0.79	0.316	0.1185
		NO_2	0.065	0.054	0.048	0.01728	0.00576
		SO_2	0.053	0.049	0.04	0.0132	0.0092
22 August 2022 12:00	48.50216, 44.57763	CO	1.469	1.350	1.08	0.3888	0.27
		NO_2	0.105	0.089	0.077	0.02849	0.01155
		SO_2	0.118	0.104	0.09	0.0279	0.0135
22 August 2022 14:00		CO	0.792	0.667	0.57	0.2223	0.0969
		NO_2	0.043	0.041	0.033	0.00957	0.00825
		SO_2	0.156	0.143	0.12	0.036	0.0228

Shannon's classical probabilistic approach was used to compare the level of uncertainty when making decisions on the choice of measurement sites. Environmental engineers (experts) made a choice of acceptable terrain for sending a mobile laboratory from 43 places of alleged measurements obtained using the existing method of forming an observation plan and from 10 according to the proposed method. A fragment of the results of the experiment is shown in Table 3.

Table 3. Comparison of the level of uncertainty when choosing measurement sites using the existing and proposed methods.

No.	Acceptable Terrain for Measurements According to the Existing Plan Formation Method	Unacceptable Terrain for Measurements According to the Existing Plan Formation Method	Entropy with the Existing Method	Acceptable Terrain for Measurements According to the Proposed Method of Plan Formation	Unacceptable Terrain for Measurements According to the Proposed Method of Plan Formation	Entropy with the Proposed Method
1	23	20	0.996	9	1	0.47
2	17	26	0.968	10	0	0
3	32	11	0.820	8	2	0.72
4	23	20	0.996	8	2	0.72

The prerequisites of the current study related to the assessment of the impact of emissions from industrial enterprises and power plants on environmental quality are relevant in various regions of the world. Similar studies of air quality monitoring using multi-criteria decision-making are carried out both for individual countries, for example, in Turkey [107], and along vast economic corridors, for example, between China and Pakistan [108]. At the same time, air quality is predicted based on infrastructure and weather data [109].

Research of S.A. Abdul-Wahab [110] became the ideological basis of this work. Therefore, the proposed approach is completely in the trend of modern world-class developments related to modeling the distribution of atmospheric air quality monitoring stations using decision support systems [111].

Modeling of spatial variability in the distribution of air pollutants and the organization of mobile monitoring presented in [112,113] testify to the relevance of the approach proposed in this article. Such solutions make it possible to increase the efficiency of air quality control in cities in comparison with stationary laboratories [114].

4. Conclusions

The study carried out makes it possible to implement the problem of decision-making on the choice of the actual place of measurement by a mobile environmental monitoring laboratory. Criteria and sub-criteria for estimating the weights of individual areas of the terrain are formulated for these purposes. The structure of the components and the relationship of their elements are demonstrated.

The results of theoretical work became the basis for the development of the architecture of the decision support system, including the formation of pollutant concentration maps, as well as decision support in the formation of an observation plan for mobile laboratories. The results of computational experiments and the operation of the decision support method on the example of the Volgograd agglomeration, Russia are given to demonstrate the operation of a software package created on the basis of the proposed approach.

A smart sustainable environment involves more than just identifying polluted air. Pollution must be registered with a verified laboratory in order to hold accountable those responsible for causing damage to the environment and, most importantly, to form a knowledge base on pollution, on the basis of which it will be possible to make the most accurate predictive models. The article describes the developed universal method for assessing environmental pollution, in which, if necessary, various methods for modeling atmospheric air pollution, air quality indices, etc., can be used depending on the accepted region or country standards.

Further scientific research in the field of maintaining the sustainability of the atmosphere of the urban environment is associated with the development of intelligent systems for solving applied problems in the field of ensuring the quality of atmospheric air. It is also necessary to improve approaches to making managerial decisions in the study of urban development projects based on databases containing archives of maps of atmospheric pollution concentrations. The next level of problems is associated with the need to combine the tasks of ensuring a favorable state of atmospheric air in the city with the tasks of creating conditions for increasing the economic efficiency of enterprises that are large consumers of energy, and therefore the balance of energy use and harm to the sustainable development of urban areas.

Author Contributions: Conceptualization, N.R.; methodology, N.R., N.S. and T.E.; software, N.R.; validation, N.R., T.E. and A.I.; formal analysis, N.S. and T.E.; investigation, N.R. and N.S.; resources, N.S. and D.P.; data curation, N.R. and T.E.; writing—original draft preparation, N.R., N.S. and T.E.; writing—review and editing, D.P. and A.I.; visualization, N.R.; supervision, D.P.; project administration, D.P.; funding acquisition, D.P. All authors have read and agreed to the published version of the manuscript.

Funding: The study has been supported by a grant from the Russian Science Foundation (RSF) and the Administration of the Volgograd Oblast (Russia) No. 22-11-20024, https://rscf.ru/en/project/22-11-20024/ (accessed on 2 February 2022).

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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