Abstract: In this paper, a methodology of geoinformation approach to mapping of atmospheric pollution of the air basin of Almaty city is developed. The proposed method of presenting data on pollution in form of an algorithm allows building a map of contamination of the surface layer of the atmosphere closest to the actually observed one. Designed object-oriented method of presentation of environmental pollution in the form of dynamic GIS models can be used when modeling the ecological status of any area, megalopolis, i.e. where spatial data, distributed in time, is used.

Keywords: geographic information system; geographic information technology; simulation modeling; object-oriented method; the dynamic model; monitoring; megalopolis; environmental condition

1 Introduction

One way to study the state of the environmental situation of megacities is monitoring via geoinformation technologies. The development and use of dynamic models of GIS of pollution zones will not only generalize, rank and organize diverse information obtained as a result of the monitoring, but also actively use it for environmental monitoring and control.

There are a number of observation networks in the territory of Almaty city belonging to different services, which are separated by departments. The task of preparation of evaluations, forecasts, criteria for selecting alternatives of management decisions on the basis of the region’s departmental data becomes, in general, undefined. In this regard, central problems of environmental monitoring are ecological economic zoning and the choice of “informative indicators” of ecological state of territories to test their system adequacy [1–4].

For creation of environmental monitoring southern capital of Kazakhstan, the city of Almaty was chosen. It is one of Kazakhstan’s most polluted cities. Almaty is characterized by a rather complicated ecological situation due to its location in foothills basin.

2 Formulation of the problem

Let Bostandyk district of Almaty ABR with a boundary S at points $r_i$ ($i = 1, 2, \ldots, n$) have 22 industrial object - $A_i$, which emit $B_i$ ($i = 1, 2, \ldots, n$) amount of harmful emissions every second, the composition of which, for simplicity, we assume to be the same.

According to the geographical location of the Bostandyk district of Almaty the entire southern border of the district is in contact with the Trans-Ili Alatau mountain chain, the northern, western, eastern borders of the area are contact with the rest of the city. Considering the aver-
age direction of the wind rose in Almaty the main powerful wind direction 20% is north.

Figure 1 shows a diagram of conventional ecological zones of Bostandyk district ABR and the location of existing industrial facilities and emissions on it.

Figure 1: Scheme of ecological zones in ABR area with a boundary S with enterprises and emissions.

According to the scheme (Figure 1), in the ABR there are \( m = 22 \) ecological zones \( ABR_k \) \((k = 1, 2, \ldots, m)\), for each of which a maximum permissible concentration of harmful substances that can be emitted during a time interval \([0, T]\) is specified, where \( T = 1 \) year, \( i, j, k \)-vectors of velocity of air particles as a function of \( x, y, z, t \), that is, the transfer of the substance along the area of air particles while maintaining its intensity is given by the equation of diffusion of substances of \( n \) industrial facilities [5].

\[
\frac{d\varphi}{dt} + \text{div}\varphi + \sigma\varphi = \frac{\partial}{\partial z}v\frac{\partial\varphi}{\partial z} + \mu\Delta\varphi + \sum_{i=1}^{n} B_i\delta(t - t_i)
\]  

(1)

where \( \frac{\partial \varphi}{\partial z} = 0 \) on the right side of the equation is the transfer of the substance along the study area of the air particles or in expanded form (2),

\[
\frac{d\varphi}{dt} + u\frac{\partial\varphi}{\partial x} + v\frac{\partial\varphi}{\partial y} + \omega\frac{\partial\varphi}{\partial z} = 0
\]  

(2)

For the lower part of the atmosphere the law of conservation of mass is fulfilled with high accuracy, expressed by the equation of continuity

\[
\frac{du}{dx} + \frac{dv}{dy} + \frac{d\omega}{dz} = 0
\]  

(3)

as a result we come to the following form of the equation (4)

\[
\frac{d\varphi}{dt} + \text{div}\varphi = 0
\]  

(4)

Let div\(u = 0\), then, given that

\[
\omega = 0 \quad \text{when} \quad z = 0, \quad z = H
\]  

(5)

where \( \varphi = (x, y, z, t) \) – the intensity of harmful substances migrating with air flow in the atmosphere. We add the initial data to the equation (4)

\[
\varphi = \varphi_0 \quad \text{when} \quad t = 0
\]  

(6)

And conditions on the border \( S \) of the area ABR:

\[
\varphi = \varphi_s \quad \text{on} \quad S \quad \text{when} \quad u_{n} < 0
\]  

(7)

where \( \varphi_0 \) and \( \varphi_s \) – given functions \( u_{n} \), the projection of a vector \( u \) on the outer normal to the surface \( S \). The relation (7) gives a solution on the part of \( S \), where air masses with the studied substance “flow into” the ABR area. If during the propagation a part of a substance reacts with the external environment, or decomposes, then the process can be interpreted as the absorption of a substance. In this case, the equation (4) will go to the next state [6]:

\[
\frac{d\varphi}{dt} + \text{div}\varphi + \sigma\varphi = 0
\]  

(8)

where \( \varphi \geq 0 \) is a quantity that is inversely proportional to time. The meaning of this quantity will be especially transparent if we put \( u = v = \omega = 0 \) into (8). Then (8) becomes the equation \( \frac{d\varphi}{dt} + \sigma\varphi = 0 \), the solution of which is a function of \( \varphi = \varphi_{e^{\sigma t}} \). This shows that \( \sigma \) is the inverse value of the interval of time during which the intensity of the substance compared to the initial intensity \( \varphi_0 \) will decrease \( e \) times.

If the domain of the solution contains the considered sources of polluting substances \( \varphi \), described by the function \( f = (x, y, z, t) \) then (8) takes the form

\[
\frac{d\varphi}{dt} + \text{div}\varphi + \sigma\varphi = f
\]  

(9)

For the equation of the form (1) given that

\[
\varphi = f_s \quad \text{on} \quad \Sigma,
\]  

(10)

\[
\frac{\partial \varphi}{\partial z} \Big|_{z=0} = \alpha\varphi \quad \text{on} \quad \Sigma_0
\]  

(11)

\[
\frac{\partial \varphi}{\partial z} = 0 \quad \text{on} \quad \Sigma_H.
\]  

Let the initial values

\[
\varphi (r, T) = \varphi (r, 0)
\]  

(12)

Here, the components of the wind velocity \( u \) are associated at each time with a ratio of continuity

\[
\frac{du}{dx} + \frac{dv}{dy} + \frac{d\omega}{dz} = 0
\]  

provided that \( \omega = 0 \) at \( z = 0 \) \( z = z_H \); \( v; \mu \) are the coefficients of vertical and horizontal turbulent exchange, \( r_i = (x_i, y_i, z_i) \). Coefficient \( \alpha \) characterizes the probability that a harmful substance on the surface of the Earth to be released into the atmosphere again, and \( f_s \) are sources of harmful substances at \( \Sigma \).
which characterizes the sanitary dose of harmful substances, that has fallen on the surface of the ground \((z = 0)\) in the environmental area \(ABR_k\). The challenge is to find a set of projected emissions \(B_i\), which would provide annual maximum permissible dose of harmful substances pollution

\[
Y_k \leq c_k, \quad k = 1, 2, \ldots, m
\]  

(13)
on minimal economic expenses on the technological reconstruction of enterprises, that would provide a fixed volume of output at a given reduction of emissions. Along with the constraints (13) it is necessary to introduce the minimizing functional

\[
I = \sum_{i=1}^{n} \xi_i (\bar{B}_i - B_i)
\]  

(14)

where \(\bar{B}_i\) is initial, and \(B_i\) is a planned capacity of emissions, coefficient \(\xi_i\) determines the capital investments in technology, providing the output of the same volume of production while reducing emissions. Then the functional \(I\) is the total cost required to improve the technology of all enterprises \(A_i\) in the transition from emissions \(\bar{B}_i\) to the planned emissions \(B_i\). As a result, we come to the problem of finding in (1)–(3) such emissions \(B_i\), that the following conditions would be satisfied

\[
I = \sum_{i=1}^{n} \xi_i (\bar{B}_i - B_i) = \min
\]  

(15)

\[
Y_k \leq c_k, \quad k = 1, 2, \ldots, m,
\]

The problem (1)–(11), (15) can be reduced to a linear programming problem.

3 Application of GIS for spatial-temporal distribution of atmospheric emissions

GIS is a promising solution for the study of spatial and temporal distribution of atmospheric emissions of any megapolis and is considered as the main element of the ecological environment monitoring system of Almaty city in this paper.

Main sources of air pollution in Almaty:

- vehicles, including a recent increase in the number of old vehicles (used cars, trams, buses, etc.);
- a large number of industrial enterprises located within the city;
- private residential sector that uses solid fuels for heating; it takes up a considerable part of the city;
- thermal power station (TPS) located near and in the city;
- the mass construction of tall buildings, delaying airflow;
- rapid growth of the city’s population, now approaching two million;
- rapid reduction of green areas.

According to the local Vechernii Almaty newspaper [7], the annual volume of emissions into the atmosphere of the metropolis is as follows:

1. the volume of emissions from motor vehicles - 190 thousand tons;
2. industrial facilities - 3 thousand tons;
3. thermal power station (TPS) - 23 thousand tons.

Motor vehicles account for the largest share of emissions into the atmosphere, 190 thousand tons or 80 percent of the total volume, including the pollutants included in the API5 index: particulate matter (soot) - 308.8 tons/year; carbon oxides - 145,829.9 tons /year; nitrogen oxides - 17,990.2 tons/year; sulfur oxides - 1860.2 tons/year; formaldehyde - 133.9 tons/year; others (hydrocarbons, benzene, etc.) - 23 977 tons/year. When coal is burned in thermal power station combustion products are released, namely, carbon monoxide, sulfur dioxide, nitrogen oxide:

1. Carbon dioxide (CO\(_2\)) is normally formed as a result of slow oxidation of coal; it is emitted directly from coal. Secondary sources - human and animal breath, fires.
2. Carbon monoxide (CO) is formed during coal dust (when exploded 1 kg dust produces \(1.5 \text{ m}^3\) CO); coal transportation.
3. Hydrogen sulfide (H\(_2\)S) is formed during the decomposition of organic substances of municipal waste and when burning coal containing pyrite.
4. Sulphur dioxide (SO\(_2\)) is released during the combustion of a mixture of coal with other gases, mostly hydrogen, sometimes methane.
5. Ammonia (NH\(_3\)) - during nitrogenous compounds decomposition.
6. Methane (CH\(_4\)) is formed along with coal. Depending on the properties of coatings and their capacity methane may appear on the surface or remain in coal. Ordinary methane emission occurs from all exposed surfaces of coal, from pores and cracks at a speed of from small fractions of a \(\text{m}^3\) to tens of \(\text{m}^3\) per minute. The gas can be released from chipped coal and developed substances. The sudden release...
Table 1: Characteristics of the source of emissions in the atmosphere on the example of Almaty TPS-1.

<table>
<thead>
<tr>
<th>Enterprise name</th>
<th>Organization level of the source</th>
<th>Type of spatial object in the GIS</th>
<th>Emission sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>TPS1</td>
<td>Organized</td>
<td>Point</td>
<td>1. Fuel economy and fuel preparation system;</td>
</tr>
<tr>
<td></td>
<td>Unorganized</td>
<td>Point</td>
<td>2. The boiler plant: the boiler and auxiliary equipment;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Linear</td>
<td>3. Ashes and slag removal system (for thermal power station, operating on solid fuel);</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Coal warehouse.</td>
</tr>
</tbody>
</table>

of methane can take place with an intensity of 1.5 to 300 m³ per minute.

7. Coal dust (i.e. small and very small carbon particles suspended in the atmosphere or sediment) is formed during production processes associated with the destruction of coal, rock and their transportation.

Main sources of emissions into the atmosphere - thermal power stations are shown in Table 1 by types of spatial objects and the degree of organization for heating [8].

The structure of simulation models (SM) was created on the basis of GIS using object-oriented principle of building complex systems.

Contaminants spread modeling in SM is carried out for three types of sources - point (boiler), linear (city transport) and area (technological and transport equipment).

To calculate emissions from urban transport the entire length of the road was divided into linear segments (200 m long linear sources). All transport units and their specific emissions were distributed along these areas.

Area sources were divided into portions of 500×500 meters. Emissions were formed taking the technological and transport equipment working in these areas into account.

Three-dimensional objects, which can produce air pollution calculations in SM are standard sanitary protection zones (SPZ), residential areas (RA) and a set of calculation points (CP).

The calculation of the standard SPZ in the Republic of Kazakhstan assumes pollution calculation at each node of the line that makes up SPZ.

Calculation by RA implies calculation at the border points of RA, selected in the same way as for SPZ. In addition, the calculation is carried out inside RA in points built by the same rule: the distance between the points should not exceed the selected calculation step. Block diagram of the algorithm for calculating surface concentrations is shown in Figure 2 [9].

“Observation data input” block assumes input of technical and economic indicators (TEI) of production, maximum permissible concentrations (MPC), meteorological data, measured concentration values.

“Output of reporting documents, maps” block involves display of admixture concentration fields, the maximum permissible concentration areas, the identification of areas of emergency exceeding, sources identification, the definition of safe modes of sources’ operation, calculated sanitary protection zones boundaries.

According to the GIS data model, graphical data is stored in special indexed binary files that are optimized for quick display and access to them, whereas attribute data stored in tables, and the number of entries in the table is the number of graphic objects in binary files. Communication between the two types of data is performed using a common identifier field.

Figure 3 shows a separate “Creating a scenario for modeling” Block 3. The following temporary characteristics are set when specifying the scenario:

- Start time: $T_{start}$;
- Modeling Period: $T_0 = \Delta T_k$;
- Modeling step (coordinate time interval): $\Delta T = \Delta T_k$;
- The intensity of the source i: emission portion for $T_1$;
- Frequency of variation of the i-th external action: $T_{i2}$;
- Frequency of variation of the j-th parameter of the source: $T_{j3} > T_1$;
- Decision rate: $T_4$;
- The intensity of impurities sediment: the proportion of impurities for $T_5$. 
All times are relative to $T_{\text{start}}$ and are located in the $(T_{\text{start}}, T_{\text{start}} + T_0)$ interval. In addition, all times are greater or equal to $\Delta T$.

Sixth to ninth blocks match the calculation of wind speed by directions, the calculation of maximum concentrations fields, the creation of an integrated surface, pollution zones and construction of concentration fields, whereas blocks 13 and 15 correspond to the main stages of the implementation of concentration calculation methods, i.e. construction of a model of pollution areas, the imposition of a pollution zones model on surfaces. In "Overlaying pollution model on a surface" block geographic data analysis functions are used:

- Recognition of the overlapping areas (polygons);
- Creation of geometric union of polygons;
- Determination of the line of intersection;
- Creation of a buffer zone;
- Search for points of contact of a linear object;
- Search for nearest spatial object by calculating distances to objects area;
- Searching for objects that fall into a particular area;

- Determination of the center of a polygon, covering a certain area.

In the block "Subsidence" the density of air, the density of matter, particle size of the substances, coefficient of impurity washout by precipitation and other parameters are taken into account.

In block 14 checking of the adequacy of the actual pollution model observations is carried out. To initially set up a model, a number of the control (basic) calculations are carried out, the results of which are judged on the consistency and coherence of its construction. If necessary, the model is corrected and the control calculation is redone.

According to studies, the reliability of the results are largely influenced by the accuracy of the representation of meteorological parameters (i.e., the accuracy of the initial data of model). Accuracy of forecast also depends on the temporary parameters of model scenario.

The simulation model, that passes the adequacy check, can be used to solve the current problems of atmospheric monitoring (environmental monitoring, pollution forecasting, decision support for the management of production and others).
Furthermore, based on GIS integration of meteorological, technical, economic information and geographical data on the territory of the city is carried out.

The basic functionality of the simulation model are as follows:

- modeling of the spread of contamination for any period for a given geographic area (SSZ, living area, a group of calculation points, etc.) and source (s);
- the formation of a dialogue of complex queries and fetching data from the database of attribute data;
- search data by referring to the stored information through requests for a cartographic image on a display;
- presentation of the results of the above actions in the form of thematic maps, tables and charts;
- zoning by allocating color objects on a map in accordance with a given range of parameter values (for example, concentrations of the pollutant substances) and others.

Analysis of the information in Table 1 and Figures 2–4 shows that the proposed method of presenting the data on pollution, which is implemented in the simulation model, allows to build a contamination map of the surface layer of the atmosphere closest to the actually observed one. This is explained by a more accurate reproduction of the dynamics of processes such as the formation of emission, transfer, subsidence of impurities.

Testing the developed models and methods based on the data of atmospheric pollution of Almaty showed the adequacy of the proposed approach in this paper.

Object-oriented approach for building a simulation model allows to create and use libraries of typical model modules that will reduce the dimension and complexity of design, and to make the simulation model an open system.

4 Conclusion

The basic functionality of GIS monitoring of ecological state of the megapolis simulation model is as follows:

- modeling the spread of contamination for any period for a given geographic area (SPZ, residential area, a group of calculation points, etc.) and source (s);
- formation of complex inquiries and sampling from attribute database in form of a dialog;
- search for data by referring to the stored information through requests for a cartographic image on a display;
- presentation of results of the above mentioned actions in the form of thematic maps, tables and charts;
- zoning by allocating color objects on a map in accordance with a given range of parameter values (for example, concentrations of the pollutant substances) and others.

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