Geoinformation software for environmental and climatic monitoring

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The content and structure of geoinformation software for environmental and climatic monitoring are determined, as well as requirements on a database allowing compilation of dissimilar information obtained in interdisciplinary investigations. The modular structure of a geoinformation system and database is described. The geoinformation software including the systems of main and thematic digital maps for the territories under study is considered. Processing of satellite images, development of applied codes for simulation in the context of geoinformation package, and the use of the results of numerical simulation are discussed.

Introduction

The present-day approach to sustainable social-economic development of any territory, in particular, Siberia,[1,2] requires fast and comprehensive analysis of complete and reliable information on the state of the environment, regional climatic and ecological changes, and the possibility to use different models and versions of prediction of such changes. In this connection, the accumulation, storage, and processing of large arrays of dissimilar climatic and ecological data, as well as fast and vivid display of the results of processing and analysis of the obtained data with the use of up-to-date information technologies are of prime importance.

Practical analysis of long-term instrumental observations of the climate and environment indicates significant spatial inhomogeneity in the processes under study with the characteristic scales of several hundreds of kilometers (for example, focal character of accelerated warming in some regions of Siberia[3]). The need in detailed study of large natural formations like the Great Vasyugan Bog becomes equally important.[4] Now these problems can be successfully solved with application of geoinformation systems (GIS)[5–10] representing the class of automated information systems with spatial (geographic) reference of the stored information. Traditionally, GIS, which are widely used in the world practice, include databases and software for automated processing and display of cartographic information.[10–13]

When developing such systems for climatic and ecological monitoring, one should keep in mind some significant requirements.

The first is the need in justified revealing of leading natural or anthropogenic factors in every region and, consequently, formation of the developed system of mathematical models for analysis and prediction of climatic and ecological state of some region, as well as for simulation of different physical, chemical, and biological processes.

The second requirement is connected with the need in monitoring of not only mean parameters of the environment and climate, but also their dynamic characteristics, i.e., the rate of change of these parameters and other time characteristics.

The third requirement is determined by the fact that along with the data obtained through instrumental measurements (observations) of variation of characteristics of the atmosphere and ecological state of environment, the expert information becomes increasingly important in the analysis and prediction of the climatic and ecological state, i.e., information, based on the experience and intuition of specialists (experts), which is commonly accumulated in knowledge bases of expert systems.

These requirements motivate development of corresponding methodical approach to creation of some geoinformation system for integration of dissimilar climatic and ecological information, which can be accumulated and stored in a GIS in the form of models, databases, and knowledge bases. Such databases should include information on individual priority objects of climatic and ecological regional monitoring and ecological state of the territory, i.e., on concentrations of chemical pollutants and their medical and biological properties, sources of technogenic pollution, etc. GIS also must contain program packages for simulation and prediction of environment state and applied programs of the GIS users.

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1. Methodological problems of designing GIS for environmental and climatic monitoring

1.1. General characteristic of GIS technologies

Let us consider the technologic problems of the processing of dissimilar climatic and ecological information. The experience of operation of computer systems, in particular, GIS, has shown that the efficiency of such systems is largely determined by the technology of information processing beginning from the time of some request reception to the time of the result output. By requests we mean here not only thematic requests for information search in databases, but also requests for some operations, for example, construction of regression models using the data on the state of an individual priority object of monitoring.

In the geoinformation literature, the technologies effected by way of GIS are called GIS technologies.[9] The GIS technology is a combination of the information technology for solution of particular user problems and the corresponding program and technical means of a GIS. The information technology is a combination of input/output, processing, storage, and search operations, which are executed in a sequence determined by the tasks of GIS users. When projecting a GIS technology, one should take into account the following requirements:

– continuity of the process,

– rational combination of manual and automatic methods of processing the information (with the use of dialog interface);

– minimal duplication of information in data files;

– single processing of information with its multiaspect use for solution of diverse problems.

The geoinformation software for the problems of comprehensive environmental and climatic monitoring with the use of GIS technologies is a modular system. It should combine diversified information resources containing four most important components: databases, digital maps, models, and analysis and prediction systems. The generalized structure of a GIS for comprehensive monitoring is depicted in Fig. 1.

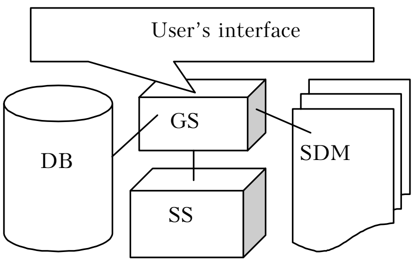

Fig. 1. Generalized structure of GIS: database DB, GIS general software GS, specialized software SS, and the system of digital maps SDM.

The general software includes programs (units) for input and editing of digital, text, and graphical data, transformation of data from different formats to the GIS format, formation and control of tabular and graphical databases, model calculations, visualization of graphical material, etc. The GIS general software commonly uses the means of one of geoinformation systems that allow the information of interest or the results of its processing to be displayed in the most convenient form about some spatial coordinates.[10] As the GIS general software, we use the ARC/INFO vector system, which is the most popular in the world, and its PC version ArcViewGIS,[11–13] which includes the database management system and supports the data format compatible with dBASE IV.

The specialized software in this geoinformation system is intended for the problems of the information input and processing with the use of GIS means for simulation, comprehensive analysis, and prediction of natural and technogenic impact on the environment, as well as other applied programs. Therefore, the specialized software (SS) includes the procedures for simulation of the processes of some object functioning and the processes of its interaction with other environmental objects involved in nature management. The software can be represented by computational procedures or modules both built-in and independent, but having the initial and boundary conditions determined by monitoring problems.[17] In the second case, the results needed for further use are transferred, using the Internet technologies, through the GIS user's interface. Besides, in the problems of monitoring of territories, an important role in the SS belongs to the programs of comprehensive analysis of multidimensional data using the data clustering methods and statistical methods, in particular, the methods of correlation, factor, and frequency analysis. The applied modules and programs for data processing, as well as the results of numerical simulation are included in the GIS environment with the use of the Avenue language for ArcViewGIS.[13]

1.2. Development of database structure and applied programs

When developing geoinformation systems and GIS technologies oriented at solution of complex problems of regional nature management, an important stage is a conceptual analysis[14] of the GIS subject domain and problem area. The subject domain (SD) is a set of objects, subjects, and phenomena of the real world, the information about which is accumulated and stored in GIS databases and knowledge bases. The problem area (PA) is a set of related problems, whose solution is the aim of a given GIS. According to the methodology presented in Ref. 14, the result of conceptual analysis of the SD and PA is, respectively, the tree of problems and sub-problems and the hierarchic modular structure of databases (Fig. 2).

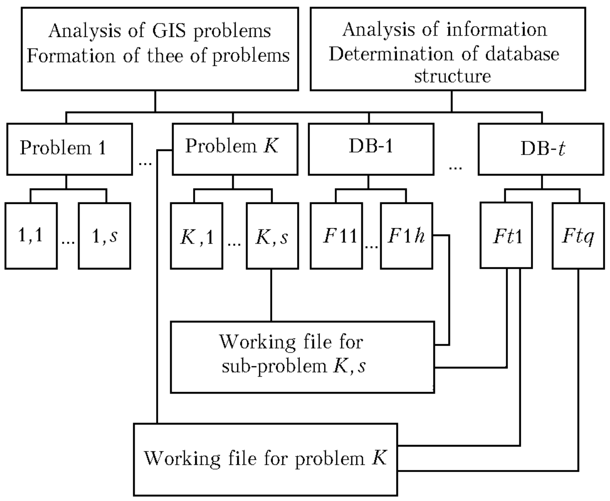

Fig. 2. Scheme of formation of a tree of problems, structure of databases, and working files for solution of problems: DB-i is the ith database; K, s is the sth sub-problem of the Kth problem; $F_{i,j}$ is the jth file of the ith database.

Based on the analysis of description of the subject domain, the list of its main components and relations significant from the viewpoint of solution of users' problems are determined. Besides logical relations like "the whole–a part" and "class–type," one more type of logical relations is introduced, namely, associative relations between SD characteristics (properties), joint use of information about which is needed for solution of every particular user's problem. The working files of problems (sub-problems), including lists of characteristics needed for solution of every problem (sub-problem), are formed of files $F_{i,j}$, $i = 1, \ldots, t$; $j = 1, \ldots, m$.

To be noted is a peculiarity of the conceptual analysis of PA aimed at construction of a tree of problems: problems are decomposed down to the level, at which elementary sub-problems are set off. Some sub-problem is called elementary, if it corresponds to a computer program executing a complete elementary procedure of processing a limited set of simple files (two-dimensional data tables). Every level of decision making in accordance with the tree of problems has its own cartographic level, what assumes formation of a GIS cartographic database as a modular hierarchic system.

2. Development of GIS technologies for solution of problems of climatic and ecological monitoring

2.1. Procedures of modeling the monitoring objects

The existing geoinformation technologies usually oriented at the processing, storage, and use of large data arrays imply mapping of territories, as well as organization and control of large dissimilar ecological (natural resource and natural protection) databases. Development of technologies aimed at solution of the problems of analysis, diagnosis, and prediction of the climatic and ecological state of a region is complicated by the fact that such information is available only for a limited number of sites at the territory of Siberia. Therefore, empiric information is deficient for "learning" models (numerical determination of model parameters). To avoid these difficulties, our GIS technology is based on the idea of using the aggregated imitation models proposed in Refs. 14 and 15 (Fig. 3).

It should be noted that the conceptual analysis of the subject domain is directed at construction of the SD model, which is a generalized idea on the subject domain with allowance for information requirements of end users. Since the users' requirements are formed based on the analysis of a set of applied models, the stage of development of the conceptual model of the subject domain of the object of monitoring coincides in time with the stage of formulation and analysis of the applied problem.

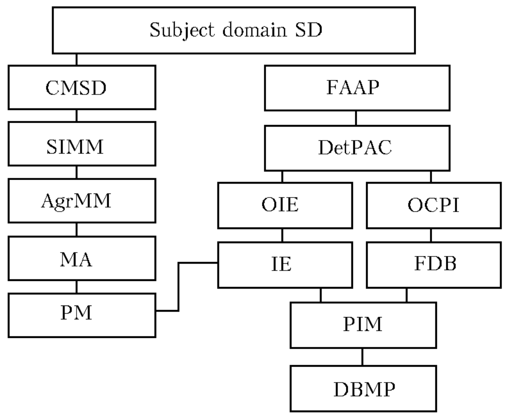

Fig. 3. Generalized scheme of GIS technology of modeling the object of monitoring: object of monitoring OM; subject domain (natural and economic system as an object of modeling) SD; conceptual model of the subject domain CMSD; structure identification of the mathematical model SIMM; aggregation of the mathematical model AgrMM; modeling algorithm MA; programmed model PM; formulation and analysis of the applied problem FAAP; determination of PA characteristics DetPAC; imitation experiment IE; organization of the imitation experiment with the aggregated model OIE; organization of collection and preparation of information about the object of monitoring OCPI; formation of databases of OM characteristics FDB; parametric identification of the model PIM; database of model parameters DBMP.

Note also that analysis of applied problems not only reveals significant concepts – SD objects and relations between them, – but also determines the main, significant from the viewpoint of user's problems, characteristics of the subject domain as the object of simulation. Revealing of these characteristics allows us to rationalize the procedures of organization of the imitation experiment with the model and the procedures of acquisition, processing, and preparation of information for "training" the model based on the available empiric information. The problems of structural identification of the model, aggregation of the model, development of the modeling algorithm, and the computer model are also important from the viewpoint of development of the mathematical model. The aims of structural identification of the imitation model are the following:

– recognition of the graph structure of the imitation model;

– determination of the form of the mathematical equations of the model and/or logic structure of the algorithms comprising the model;

– determination of a set of model parameters.

Our analysis has shown that methods of traditional modeling based on decomposition of the modeled object require a large number of model parameters for their description. Just this does not allow the idea of the model training to be implemented using the available empiric data (as a rule, the amount of such data is limited for systems of the considered class). In this connection, the problems of our interest should be solved using the structural information contained in the conceptual model not directly as a scheme of decomposition of the subject area with respect to its composition and properties, but as a transformed (aggregated) model allowing one to decrease significantly the number of model parameters. Aggregation of the model is aimed at the search for such its structure, which allows one to describe adequately the object at a minimum of model parameters. This assumes transformation of both the model structure and the form of the equations to obtain the minimal set of model parameters. The requirement of minimization of the number of parameters in the imitation model is motivated by the need in estimation of the parameters from empiric data on the characteristics of the modeled object in conditions of deficiency of such empiric information. Thus, the aggregation of the imitation models assumes a decrease in the number of model parameters through transformation of the model structure.

The proposed procedure of constructing aggregated models is based, first, on the use of qualitative information obtained from the theoretical analysis of properties of the object's parts, isolated through the object decomposition and, second, on the use of quantitative empiric information represented in the form of maps and statistical materials and obtained from field experiments and observations. Consequently, when composing ("assembling") the aggregated model, its minimal structure is determined from consideration of most significant properties and interactions between the elements, which are reflected in the model through specification of abstract model parameters, which can be estimated only from empiric data.

The problems of parametric identification of the model acquire particular importance in the modeling. The aim of identification is estimation of model parameters from empiric data.

Traditional methods of identifying dynamic objects used in technical cybernetics are based on obtaining of excessive information on the object through repetition of the experiment under different initial conditions, external impacts, and random factors in order to get the information excess with respect to the sought model parameters. In the process of estimating (identifying) model parameters, this excess is eliminated during processing of the obtained experimental data by probabilistic methods depending on the statistic peculiarities of selected data on the object's characteristics. The proposed approach to the parametric identification of the model (under conditions of deficient empiric data on the object of monitoring) assumes an excess of model data and "fitting" of model parameters to empiric data.

2.2. Procedures of spatial analysis of data

When processing the data on the state of the environment and natural resources, we used the algorithms for spatial analysis of data in GIS based on the traditional statistical methods, for example, the principal-factor method, and the algorithms of computer geozoning of some territory[16] based on the methods of pattern recognition and automatic classification. To solve the problem of geozoning in our formulation, when neither the number of classes nor thresholds of spread of characteristic values are known in advance, the use of well-known automatic classification algorithms turns to be insufficient. In this connection, we had to develop the modified automatic classification (AC) algorithm with predetermination of the number of classes depending on properties of the classified zones (geoquanta) and to formulate the AC stop rule.

The modified AC algorithm has been developed based on the idea of revealing the natural number of classes, which can be determined for every set of real objects. It is known that the spatial structure of natural complexes being a subject of matter of geography, geology, biology, and other relative sciences shows the characteristic spatial scales of grouping these objects: large-scale, mesoscale, and small-scale structures (for example, the structures of the first, second, and third order in geology). When processing information arrays connected with the quantitative description of such complexes, classification of objects reveals rather stable spatial groups of objects only slightly depending on characteristics of an information array. Such stable spatial groups (clusters) form the basis for determination of the natural number of classes, which can be laid in the foundation of the stop rule in the modified AC algorithm (Fig. 4).

This procedure allows zoning of the territory with respect to an arbitrary set of dissimilar indices, what is important in the problems of comprehensive analysis of the state of the environment and natural resources. *At the first stage* of the geozoning procedure, files of initial data are compiled. These files store the information about characteristics of elementary parts of the territory – geoquanta. *At the second stage*, the geoquanta are automatically classified, i.e., divided into classes according to the predetermined set of values of their characteristics. The degree of statistical stability of the classification with respect to the accuracy of measurements of the geoquanta characteristics is estimated. *At the final stage,* the geoquanta, falling in the same class by the degree of their spatial closeness (connectedness), are grouped into homogeneous zones and descriptions of representatives of every zone are formulated.

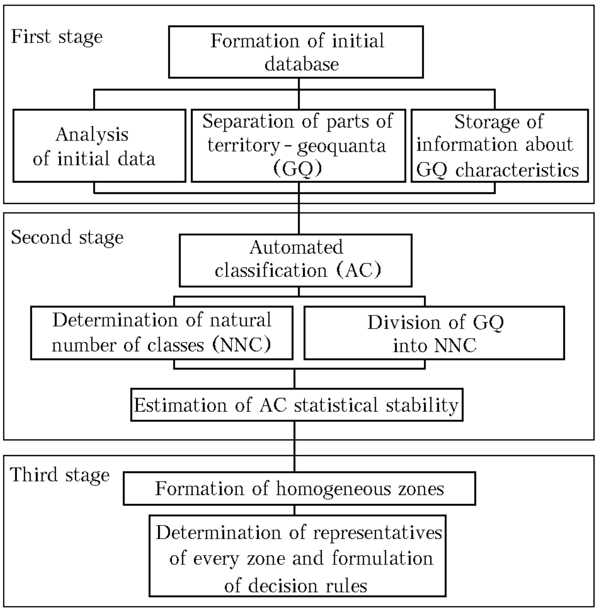

Fig. 4. Sequence of operations in geozoning.

3. Database

The information in the GIS databases is, in the general case, the result of work of a multidisciplinary team of investigators from many research organizations, as well as federal and territorial institutions and bodies, therefore the databases have a modular structure and can be spatially distributed. In addition to data themselves, the databases should contain metadata, i.e., data descriptions. Therefore, for correct access to the information, the following main requirements on the database formation were formulated:

1. MS Access or dBASE VI with Code Page 1251 are used for data input and storage.

2. Every database table should have a description in the form of a set of metadata with every field described in detail.

3. The database should have a structure allowing addition of new tables without changing the existing tables and logic relations between them.

Figure 5 shows the logic structure of the database for storage of information – *results of observations*. *Parameters of observation* are the quantitative and qualitative indices characterizing the state of natural objects or climate near *observation sites* at certain time.

Observation sites have certain geographic arrangement and are referred to the digital map, and all other data from the database are referred through the relations specified in the database.

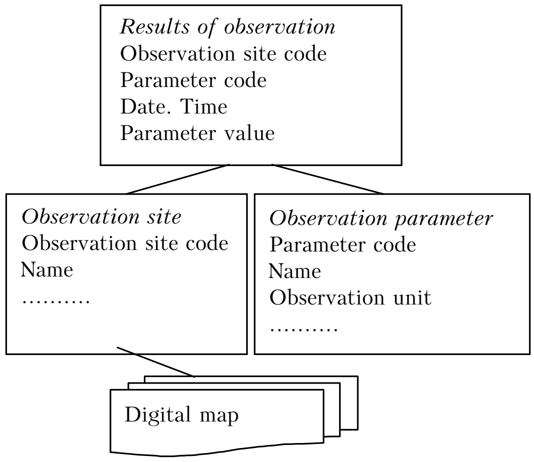

Fig. 5. Logic structure of the database.

4. System of digital maps and use of space information at comprehensive monitoring of environment

Since the use in comprehensive monitoring of dissimilar information on natural resources and ecological situation requires accounting for its spatial properties (administrative, landscape, and specific zoning, geographic reference of towns, villages, observation sites, etc.), the GIS contains various-scale digital maps. The system of digital maps includes the topographic basis and thematic layers. As a digital topographic basis, the 1:1000000 licensed map of Russia (produced by Roskartografiya) is used, which is converted from the F1M format to the ArcView GIS format and attendant by the bases covering hydrology, flora, transportation networks, population, soil, relief, and administrative boundaries. This topographic basis is continuously supplemented with new information layers needed for solution of the problems of comprehensive environmental and climatic monitoring. For some parts of the territory under study with large natural objects (for example, Great Vasyugan Bog, flood-lands of Ob River) or large-scale anthropogenic impact (for example, oil and gas production regions of Western Siberia), the larger-scale digital maps were made. The most efficient and promising tool for map acquisition is now aerospace surveying the Earth's surface with following digitization and vectorization of the results using geoinformation technologies. In particular, we compiled a set of space images of different areas of the Great Vasyugan Bog (GVB) zone and the main oil production regions of the Tomsk Region, made from aboard Resurs-01 satellite.

Figure 6 shows the coverage of the GVB territory by high- and medium-resolution space scanner images of the Earth's surface (MSU-SK scanner, resolution of 175 m; MSU-E scanner, resolution of 35–45 m).

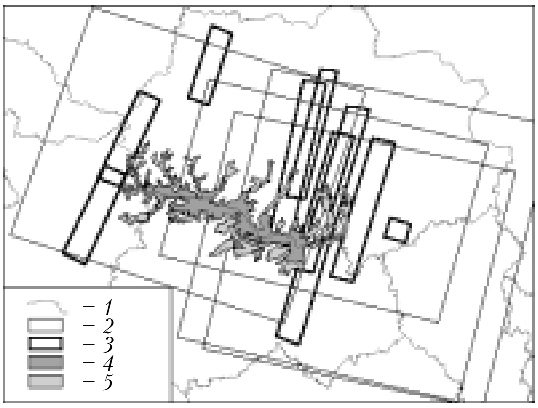

Fig. 6. Coverage of GVB territory with space images: administrative boundaries *1*; image boundaries: MSU-SK scanner *2*; MSU-E scanner *3*; central part of the GVB *4*; GVB spurs *5*.

Since the forest-marsh ecosystems, whose comprehensive studies are complicated by their hard-to-reach inhabitation, dominate at the territory of Western Siberia, a methodically important problem is a correct determination of the boundaries of forest and marsh areas from the space images. Remote sensing allows us to update the available data (for example, the forest estimation is carried out once in every ten years), eliminate the errors in landscape interpretation of the forest estimation, correct the set of decoding indices, and determine the areas of priority for the ground-based study.

The idea of using the space imaging to determine areas of different-breed forests is based on the fact that different landscape areas have different brightness when observed from space. In space images, the brightness scale is shown by different colors. Based on the color difference in a space image, we can separate homogeneous surface zones. Using three-zone (two zones in the visible region of the spectrum and one in the infrared) space images with a spatial resolution of about 40 m obtained from the Resurs-O satellite with application of GIS technologies and the ERDAS Imagine processing system,[17] we can separate rather reliably marsh and forest areas with different forest breeds.

For example, the procedure of processing the digital satellite images of the Vasyugan Bog territory includes the following stages:

– determination of the region, at which different areas (forest, marsh, mixed) will be recognized;

– selection of a space image covering this region completely or partly;

– reference of the image to the digital map with the use of ERDAS Imagine;

– clusterization of the image (by roughly 30–70 indices; the number of indices is chosen in such a way that different landscape areas do not fall in the same class);

– coloring of separated zones with ERDAS Imagine using the colors corresponding to determined forest breeds.

The ERDAS Imagine system serves for reference of the satellite image to the map, image clusterization, and recognition of areas. The GIS is used for vectorization of the satellite image after recognition of landscape areas and cartographic mapping of the results of processing of the space information. At the stage of clusterization, the forest breed dominating in the considered region is separated in the first turn, then it is used as a basic one in the process of recognition of landscape areas.

5. Complex of mathematical models

Comprehensive monitoring of a complex natural object needs a system of applied programs as a part of the geoinformation software for modeling the object functioning.[18] Thus, when analyzing the technogenic impact on the forest-marsh ecosystems, it is necessary to have a suit of programs for modeling the air, water, and soil spread of anthropogenic pollutants emitted due to the economical activity at the territory of interest. It is well known that there are rich resources of oil, gas, peat, wood, as well as surface and underground waters at the GVB territory. Therefore, in the process of investigation, an important role should be played by mathematical models, allowing estimation of technogenic impacts connected with the possible use of the above natural resources.

Oil production exerts the most significant influence on the state of natural ecosystems. Analysis shows[22,23] that the factors of oil production impact on the environment can be divided into three main groups. The first group includes mechanic actions, for example, road building, disrupting the surface structure, and changing hydrological conditions. The second group includes geodynamic actions due to changes in the seam pressure as a result of extraction of large oil and gas volumes from the interior of the earth and leading to geomorphological changes. However, in conditions of oil and gas production at the territories of Southwestern Siberia, most dangerous are the factors of the third group connected with chemical pollution of soil, water, and atmospheric air. The most important factor among them is the atmospheric pollution due to oil gas burning in flares all over the territory of the West-Siberian oil-and-gas province. The flares are surrounded by extended plums of aerosol pollutants. Their negative effect is intensified by fine-disperse products of incomplete combustion having toxic properties and emitted as soot in a considerable amount.

The problems of development, methodology, and organization of ecological and geographic studies at the territories of Western Siberia exposed to chemical pollution are considered in Ref. 19. The essence of the proposed integrated approach is reduced to determination with the use of GIS of landscape areas being under the effect of negative technogenic factors. This allows revealing of environmental components being in the critical state. The methodology was used as a basis for development of the program package for geoinformation simulation of atmospheric spread of chemical pollutants, which allows joint spatial analysis both of the landscape structure of the territory and the results of simulation of pollution with the use of digital maps.[20,21] The program package simplifies ecological prediction and allows one to assess the integrated effect on the environment, as well as to promptly reveal arising anomalies and make decisions on their elimination. With the use of the package, we have analyzed the effect of atmospheric pollution on a particular territory, similar in landscape structure to the GVB territory.[22–24]

An important stage in solution of hydrological and hydrochemical problems of GVB monitoring is the development of the software for geoinformation simulation of the river network, which includes a system of digital maps with the following coverage: hydrography (rivers, lakes, springs, etc.), relief, and water observation sites. The needed hydrological and hydrochemical information (water discharge, current speed, and concentration of pollutants at observation sites) is stored in the GIS database. The system of mathematical models includes the model of the river network in the form of a directed graph, the model of pollution transport by water streams in the form of a system of partial derivative equations, and the model of destruction and transformation of pollutants under natural conditions.

The model of the river network is constructed based on the digital map through transformation of hydrographic layers into the directed graph,[25] on the base of which the system of linear algebraic equations of water flow balance at network nodes is formed. To take into account the pollution spread in the river network, the system of equations is complemented with linear algebraic equations describing pollutant concentrations in water streams. Since pollutants are subjected to destruction and transformation under the effect of natural factors (biodestruction, UV irradiation), the model of matter destruction in the form of an exponential equation is used.

Conclusion

This paper generalizes the results of investigation and the experience of cooperation of investigators and developers within the framework of the Tomsk Regional GIS Center SB RAS. This cooperation is aimed at the use of geoinformation technologies in the problems of environmental and climatic monitoring of large territories, as well as scenario prediction of development of the region. Further development of this work is planned within the framework of our cooperation with the EU programs INCO-Copernicus-2 and INTAS connected with creation of integrated information-measuring systems for environmental monitoring and management.

The main directions of extension of the above geoinformation system are:

– use of European last-generation expert systems and up-to-date methods of instrumental measurements[26];

– formation of a set of databases having the identical structure and distributed over servers of different organizations, as well as organization of authorized access to the results through the information web-portal based on the set of distributed Internet sites.[27]

Another planned promising direction in development of GIS technologies follows from the problems of monitoring of global and regional natural and climatic changes. In this case, the information database must contain not only the parameters characterizing some state of natural systems, but also dynamic characteristics of the climate-forming processes. These processes, in their turn, also change under the effect of natural and anthropogenic factors. The geoinformation procedures for operation with such databases differ significantly and fall in the class of so-called temporal geoinformation technologies.[28] The development of GIS technologies in this direction is realized through specialized computational modules in a specialized software package.

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