REVISTA INCLUSIONES

TRABAJO EN EQUIPO SIN FRONTERAS

Revista de Humanidades y Ciencias Sociales

Volumen 7 . Número Especial
Octubre / Diciembre
2020
ISSN 0719-4706

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ISSN 0719-4706 - Volumen 7 / Número Especial / Octubre – Diciembre 2020 pp. 423-438

APPROACHES TO ECOLOGICAL STATUS ASSESSMENT OF URBAN TERRITORIES

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Fecha de Recepción: 15 de junio de 2020 – **Fecha Revisión**: 24 de junio de 2020

Fecha de Aceptación: 23 de septiembre 2020 – **Fecha de Publicación**: 01 de octubre de 2020

Abstract

Urban territories are marked by a high level of environmental pollution. A comprehensive analysis of pollution sources and pollutant spreading, determined by the natural conditions of the territory and the urban infrastructure, is needed to assess the environmental situation of the city. This approach regards the urban environmental situation as a dynamic medium, changing in time and space. This study aims to substantiate the approach to the integrated ecological status assessment of urban territories, based on geoinformation analysis and 3D cartographic modeling of pollutant distribution in the urban environment. The paper proposes the principles of integrated environmental assessment, including analysis of both the degree of pollution and the processes of pollutant distribution. The experimental analysis of the ecological status was performed in Novosibirsk, Russia. A digital terrain model, a digital model of terrain features that have an adverse impact on the environmental situation, and an environmental database were created. The city was zoned based on the composite indicator of the hazard level. Pollutant fluxes from the anthropogenic objects, posing environmental hazard, was 3D-modeled.

Keywords

Ecological status – Environmental assessment – Geoinformation analysis – Cartographic modeling

Para Citar este Artículo:

Trubina, Lyudmila K.; Nikolaeva, Olga N.y Moskvin, Victor N. Approaches to ecological status assessment of urban territories. Revista Inclusiones Vol: 7 num Especial (2020): 423-438.

Introduction

The socio-economic development of large cities is inevitably accompanied by greater anthropogenic impact on the territory and aggravation of environmental quality problems. It is hardly possible to successfully solve these problems unless a reliable and detailed environmental profile of an urban territory is available[1]. Building such a profile requires actual data on the spatial localization of pollution sources and pollution fields as well as on the mutual influence of technogenic and natural (in particular, climatic and geomorphological) factors.

The current methods for ecological status assessment of territories are based on calculation and analysis of quantitative indicators that characterize the pollution of a certain environment compartment. Typical examples of such indicators are the concentration of pollutants in ambient air, surface water or soil and the volume of emissions into the atmosphere or discharges into water bodies. In the process of ecological status assessment, these indicators are compared with the regulatory limits (maximum permissible concentrations, emissions, discharges, etc.) to determine if the pollution limit in a territory has been exceeded. However, at that, the assessment addresses only one environment compartment, taken individually. In instances when integrated indicators of environmental quality are determined, the interdepartmental estrangement of organizations that collect the source data often results in the inconsistency of information on the same object, which hinders reliable assessment of the existing environmental situation[2]. Even if the ecological status of objects or territories is evaluated according to the same methodology, the comparison of results would still be difficult because organizations arrange territorial observations in various ways and use different topographical bases[3].

Thus, the lack of systematic approach to the source data processing, the inconsistency of methods used in data collection, integration and analysis, and the heterogeneity of information coverage of a territory produce incorrect information on the patterns of spatial distribution of environmental strain. The use of interpolation or extrapolation can further reduce the reliability of findings.

It should be noted that in the ecological status assessment of urban territories the source data is usually collected through observations in a limited number of points randomly scattered over the city. The collected data can be sufficient to form a general idea of the environmental situation in the city in large, but they fail to provide a level of detail sufficient to assess the status of a particular district or quarter. Since the source data, collected during environmental monitoring for the ecological status assessment of urban territories, are spatially distributed, geoinformation systems (GIS) appear to be an optimal tool for the data interpretation and analysis because GIS are able to provide geoinformation analysis and cartographic visualization of the obtained findings.

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[1] L. K. Trubina “Methodological aspects of urban lands state ecological assessment”, Interexpo Geo-Sibir, num 2(3) (2012): 200–203 y L. K. Trubina & D. V. Panov “Certain aspects of considering ecological component in monitoring of urban lands”, Izvestiya Vuzov “Geodesy and Aerophotography”, num 2/1 (2012): 121–123.

[2] E. A. Kravets “Maps, “paradigm change” and answers to spatial questions”, Geodezija i Kartografija, num 6 (2013): 55–57 y E. A. Kravets, Cartography Logic (Analysis of Issues Related to State and Protection of Environment) (Moscow: Moscow State University of Geodesy and Cartography, 2010)

[3] A. N. Beshentsev “Geographic information resources: features, classification, placement”. Informatsionnyye Resursy Rossii, num 4 (2015): 21–26.

This study aims to substantiate an approach to the integrated ecological status assessment of urban territories, based on geoinformation analysis and 3D cartographic modeling of pollutant distribution in the urban environment.

One of the natural factors that have the most significant influence on the formation of environmental situation in an urban territory is the relief. The combination of positive and negative landforms as well as the difference in absolute elevation determine the gradient and the exposure of slopes, which in turn set up the consistent patterns of matter and energy movement. Morphometric features of the relief condition the direction and the extent of contamination in the surface air, the geological substrate, the surface and underground water bodies, and the soil cover.

The processes of pollutant migration along the geological substrate can be transposing (flushing of contaminants off positive landforms) and accumulating (accumulation of pollutants in depressions). A combination of transposing and accumulating processes forms hotbeds of environmental strain in an urban territory and can activate other adverse phenomena (for example, to increase the concentration of heavy metals in the urban soils due to sheetwash from a non-ferrous smelter site nearby).

GIS give vast opportunities in the study of the impact of relief on the environmental situation of urban territories. They allow building digital relief models, calculating morphometric indicators, tracing the relationships between the quantitative characteristics of the relief and the contamination levels in the geological substrate, and more.

An extended morphometric analysis of the relief can create the basis for the preliminary zoning of urban territories according to the direction and the intensity of pollutant fluxes. A comprehensive analysis of the obtained information and actual data on the ecological status makes it possible to increase the objectivity of ecological status assessment of urban territories and give the desired level of detail down to separate quarters. The spatial relationship of the selected fluxes and various functional zones of the city (or districts thereof) can be visually represented in cartographic 3D models.

Methods

To make ecological status assessment more objective, it is proposed to use the integrated approach, based on a comprehensive review of natural and anthropogenic processes of pollutant migration across in the geological substrate. Generally, there two types of fluxes of matter (Fig. 1):

- natural fluxes, i.e. processes of pollutant distribution that are determined by the natural features of the territory (mainly by the relief),
- anthropogenic fluxes, i.e. man-made channels of matter and energy transport that are formed by urban infrastructure (roads, railways, sewer collectors, district heating networks, etc.).

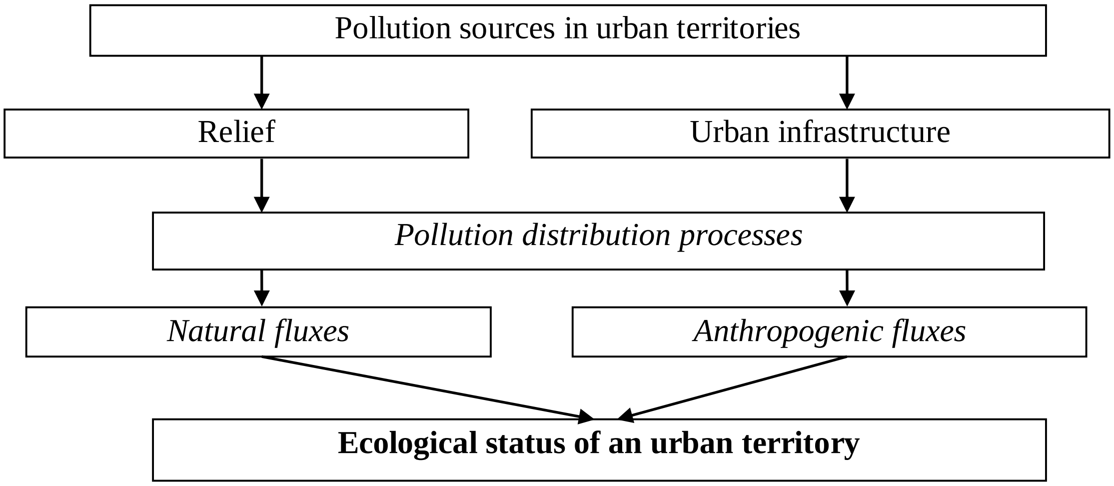

Fig.1
Influence of fluxes on the ecological status of an urban territory.

Integration of data on the natural and anthropogenic fluxes of matter makes it possible to simulate the environmental situation of an urban territory on the basis of the comprehensive analysis of disparate spatial data (Fig. 2).

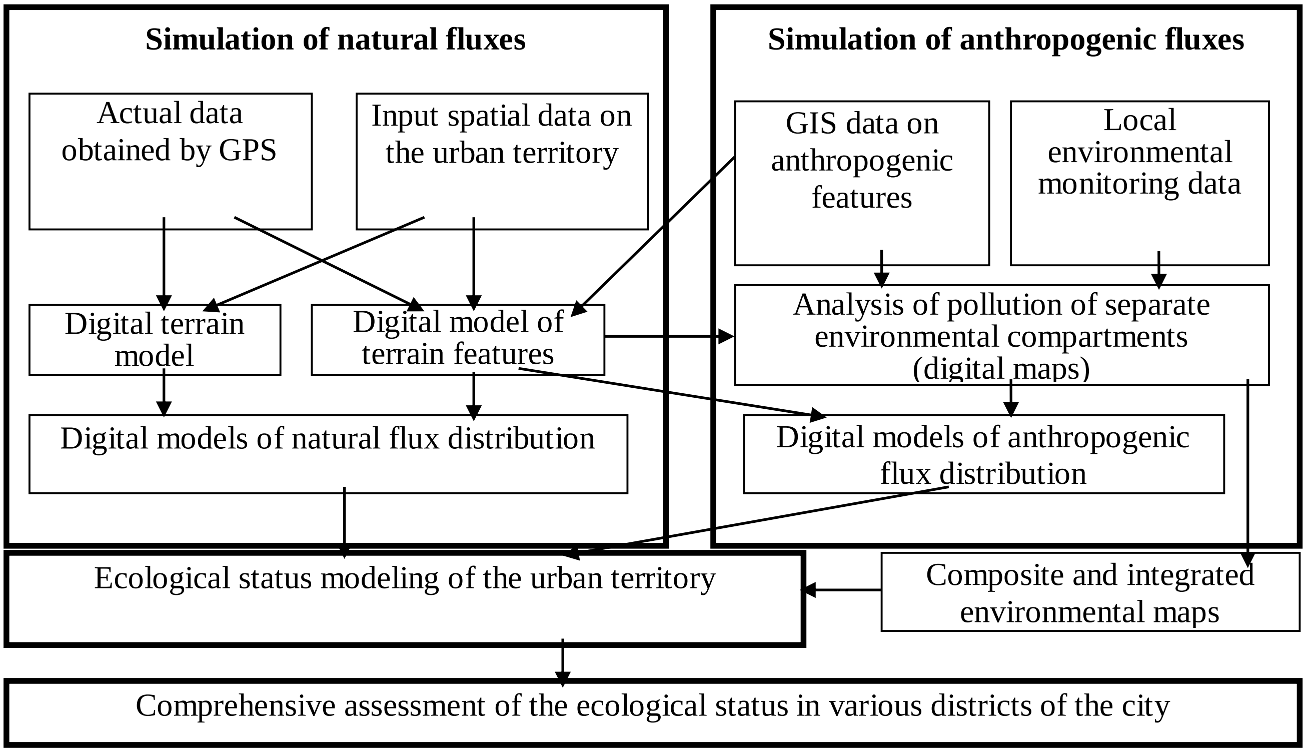

Fig. 2
Flux modeling for the ecological status assessment of urban territories.

Modeling of fluxes that occur in the urban territory is based on the following scientific and methodological principles:

- the first stage of territory analysis involves identification of fluxes that determine the spatial distribution of pollutants,
- the list of morphometric parameters to be analyzed should be sufficient to obtain the reliable characteristics of direction, speed and intensity of the transport of pollutants,
- to improve the reliability of assessment and to ensure possibility of analyzing the ecological problems of the territory, it is necessary to provide for an integrated review of the results of the morphometric analysis of relief and the spatially distributed data on environmental pollution, collected by local monitoring systems,
- to streamline the perception and understanding of the relationship between the relief features and the technogenic objects, it is necessary to provide for the three-dimensional visualization of the modeling results and the assessment findings.

The flux simulation begins with the analysis of morphometric features of the urban relief. The term ‘relief’ is used here to refer to the set of arranged landforms that emerged under the influence of gravimagnetic fields, whose action on the grounds surface is manifested in the fluxes of soil-geological matter. The primary analysis can be carried out using the method of relief plasticity, which is based on the geometric transformation of horizontal topographic contour (isohypses) into morpho-isographs[4].

The morphometric features of the relief, which can be obtained by GIS based on the analysis of digital terrain models (DTM) give the most complete description of the relief character. In most cases, such parameters as illumination of slopes and runoff factors (inclination angles, gradient, exposure of slopes, etc.) serve as the basic ones for the analysis. The speed and the direction of matter distribution (including pollutant fluxes) are estimated using the information on horizontal and vertical curvature[5]. The relief surface forms can be described in detail using various adaptations of morphometric analysis[6].

The 3D visualization is a necessary for presenting the results since it plays an essential role in perception, understanding, and evaluation of the relief features. Mapping of detected fluxed in the form of 3D surfaces helps to increase the visibility and reveal the interrelationships between the natural processes and the anthropogenic activities. The level of detail of the created DTM depends on the source materials used to obtain the relief data. The contour DTM construction is rather widespread; and, in this case, topographic maps of various scales become the principal source material[7].

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[4] I. N. Stepanov, Theory of relief plasticity and new thematic maps (Moscow: Nauka, 2006) y I. N. Stepanov, Space and Time in Soil Science: Non-Dokuchaev's Pedology (Moscow: Nauka, 2003).

[5] P. A. Shary “Models of topography”. In: Zhou Q., Lees B., Tang G. (eds.) Advances in Digital Terrain Analysis. Lecture Notes in Geoinformation and Cartography (Springer, Berlin, Heidelberg, 2008) y K. S. Rawat & A. K. Mishra “Evaluation of relief aspects morphometric parameters derived from different sources of DEMs and its effects over time of concentration of runoff (TC)”. Earth Science Informatics, num 9(4) (2016): 409–424.

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[7] E. Guilbert “Multi-level representation of terrain features on a contour map”. GeoInformatica, num 17(2) (2013): 301–324 y W. Shi; B. Wang & Y. Tian, “Accuracy analysis of digital elevation model

However, since the contours are obtained by transforming the source data (point interpolation), the resulting digital representation of the surface is somewhat distorted due to smoothing of the micro- and nano-relief forms. It should be noted that this distortion can only be significant in large-scale studies. To obtain highly detailed DTM, it is expedient to use remote sensing and laser scanning data, supplemented by field measurements, if necessary. In this case, it is possible to construct a DTM of the desired detail and accuracy[8], including DSM of territories densely covered with forests[9] or developed with high-rise buildings[10].

The second important stage in the ecological status assessment is the study of environmental pollution. The relevant source data are collected during local environmental monitoring; in Russia it is carried out by the Federal Service for Hydrometeorology and Environmental Monitoring of the Russian Federation. The collected information includes the actual data on pollution of air, surface water, soil in residential areas, etc. and the ready-made values of composite and integrated ecological status indicators (air pollution index, specific combinatorial index of surface water pollution, composite index of soil contamination with heavy metals, etc.). If the study relies on monitoring data, collected in accordance with officially approved methods, it is able to provide informative and objective results of the ecological status assessment of the urban territory.

The main principle of ecological status modeling is to take into account the type of environmental compartment under study and the type of pollution, when analyzing the spatially linked environmental information[11]. The conducted research made it possible to list the data on the environmental compartment status, which are sufficient for a comprehensive description of the state of environment, detailed to separate city quarters. The considered pollution of environmental compartments (and the phenomena that condition them) includes:

- pollution of air (emissions of industrial facilities, motor vehicles, general dust content in the ambient air),
- pollution of surface water (discharges of industrial and domestic waste waters);
- pollution of urban soils (domestic and industrial solid waste landfills; industrial facilities of ferrous and non-ferrous metallurgy; oil product, fuel and lubricant storage facilities; technogenic geochemical anomalies),

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relating to spatial resolution and terrain slope by bilinear interpolation", Mathematical Geosciences, num 46(4) (2014): 445–481.

[8] R. Bennett; K. Welham & R.A. Hill, "A comparison of visualization techniques for models created from airborne laser scanned data", Archaeological Prospection, num 19 (2012): 41–48; P. Yu; N. Eyles & S. Sookhan "Automated drumlin shape and volume estimation using high resolution LiDAR imagery (Curvature Based Relief Separation): A test from the Wadena Drumlin Field, Minnesota". Geomorphology, num 246 (2015): 589–601 y P. Tarolli "High-resolution topography for understanding Earth surface processes: Opportunities and challenges". Geomorphology, num 216 (2014): 295–312.

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[10] S. Friedman & I. Stamos "Online Detection of Repeated Structures in Point Clouds of Urban Scenes for Compression and Registration", International Journal of Computer Vision, num 102 (1) (2013): 112–128 y I. Chauhan; C. Brenner; R.D. Garg & M. Parida, "A New Approach to 3D Dense LiDAR Data Classification in Urban Environment", Journal of the Indian Society of Remote Sensing, num 42 (3) (2014): 673–678.

[11] S. S. Dyshlyuk; L. A. Romashova & O. N. Nikolaeva "On the use of environmental maps in creating environmental company spatial data infrastructure", Geodezija i kartografija, num 4 (2016): 18–25.

- noise impact generated by traffic (total impact of public, private and special-purpose transport);
- radiation background conditioned by natural factors (Radon-222 concentration in the soil air, localization of tectonic faults and outcrops of rising granite massifs).
- sources of technogenic radiation exposure (sources of ionizing radiation, areas of technogenic radioactive contamination).

The above data and the information on the relief and its character have a clear spatial localization since it is a mandatory stage of environmental monitoring to determine and fix the coordinates of new sampling points and key sites, or to link the observation results to the series of existing posts. One of the leading methods of spatially related data processing is the cartographic method. It provides effective tools for spatial data analysis, including the following types of digital environmental maps[12]:

- industry-specific or analytical maps, reflecting the contamination of an environmental compartment taken separately and recording the collected information as full as possible;
- composite ecological maps, summarizing the influencing factors and the sources that affect the main environmental compartments in the given territory (air basin, surface waters, soil, radiation background);
- integrated ecological maps, showing the level of environmental disruption in the territory in general or the level of environment-related health risk for the population.

All three types of maps are logically interrelated, and the preceding maps serve as a main source for compiling subsequent maps.

The effective record of data, collected for the ecological status assessment of urban territories, implies both composite and integrated environmental mapping of the territory. Composite maps are created to list the technogenic environmental factors, operating in various parts of an urban territory, and to identify their intensity. The comprehensive environmental description, provided by such maps, lays the informational basis for ecological zoning of the territory. The zoning results are further visualized in the integrated environmental maps.

In the process of ecological zoning, there can be reveled a comprehensive ecological status indicator, which takes into account the weight of each pollution type in the environmental compartments. Depending on the assessment purpose, the comprehensive indicator can be calculated for regular grid cells, into which the urban territory is divided at discretion, or any other unit. The weight of each pollution type is determined by the expert evaluation method. At that, the primary properties of pollutants and their weight in the integral quality should both be factored in.

Integration of the morphometric relief analysis results, presented on the maps mentioned above, makes it possible to construct *digital models of the distribution of natural and anthropogenic fluxes*. This is carried out using the basic methods of geoinformation

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analysis. What is important here is the cartographic 3D modeling of intermediate and final research findings; hence GIS should be applied as the main working tool. GIS have software modules for constructing and exploring cartographic 3D models and identifying spatial relationships between objects. Such models hold a number of advantages that are unavailable in two-dimensional cartographic products:

- good ostensiveness, which enables to form a clearer understanding of the relief and helps to identify general patterns of landform distribution over the territory,
- high informational value, which implies that one image combines a traditional 'top view' with block diagrams, longitudinal and transverse profiles and other images characterizing the internal structure of the object or phenomenon being mapped,
- wide field of view, which gives the possibility of viewing the mapped territory from any angle and hence analyzing the vertical leveling of the urban area.

These advantages turn cartographic 3D-models into an effective tool for solving research and management tasks in the field urban system monitoring.

Nevertheless, it should be noted the technical implementation of such cartographic works can be rather complex. That is why two-dimensional digital maps of the spatial distribution of natural and anthropogenic fluxes can be used along with cartographic 3D models to visualize the outcome of integrated geo-information analysis of a given relief and environmental situation in that area.

Regardless of implementation, such cartographic works add much informational value to the existing documentation, adopted for the sustainable management of urban economy[13]. The data presented in them lay the basis for a detailed assessment of the ecological status of urban territories on the basis of ecological, geodynamic, cadastral or biomedical criteria. Such data allow solving the following tasks:

- environmentally sound planning of residential areas based on the established patterns of pollution of the geological substrate,
- making recommendations on the economic use of certain parts of the territory, taking into account the identified and estimated erosion risks,
- environmentally safe planning of high-rise residential development pursuant to modeling of air pollution zones that can be created by large sources (power plants, etc.),
- amendment of existing sanitary protection zones and establishment of new ones, based on the analysis of the distribution of pollutant fluxes from operating and planned industrial facilities,
- substantiation of spatial development of various functional zones of the city (residential areas, industrial sites, infrastructure, green areas, etc.), taking into account the environmental safety and public health requirements,
- identification of priorities in the field of protection and restoration of the city's environment, making recommendations for improving the quality of life.

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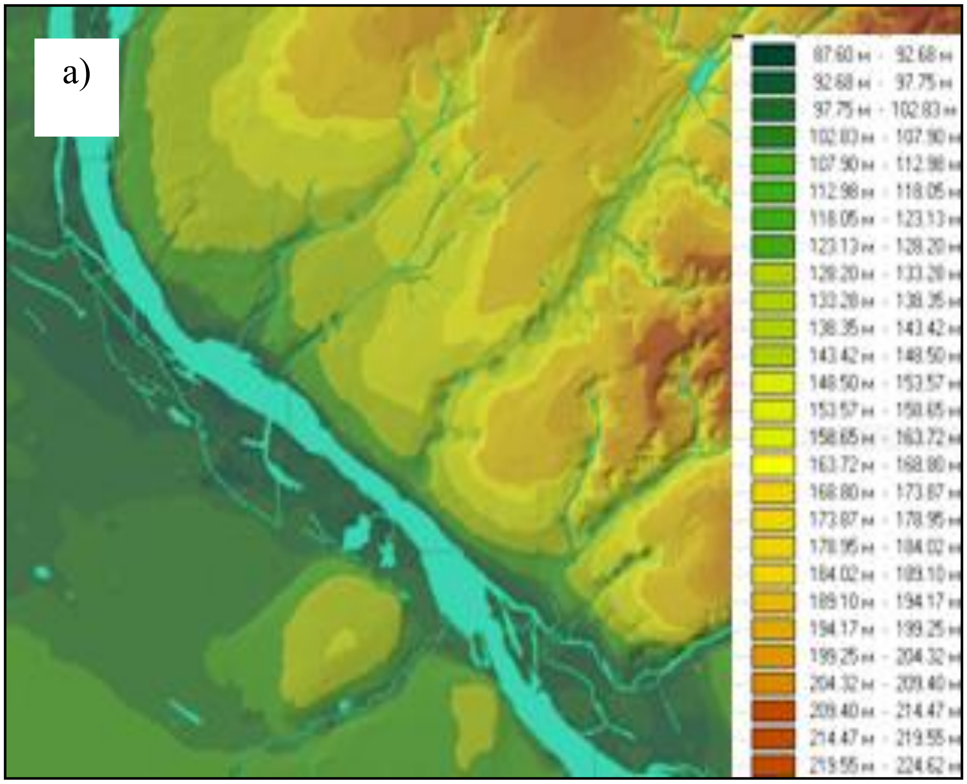
[13] L. K. Trubina; T. A. Khlebnikova; O. N. Nikolaeva & E. N. Kulik, "Integration of geospatial data on the basis of three-dimensional modeling for environmental assessment of urban areas", Izvestiya Vuzov "Geodesy and Aerophotography", num 4/C (2013): 83–86.

Results and discussions

This chapter describes the experimental study of the above approaches to ecological status assessment of urban territories. The experiment was carried out in Novosibirsk, a major industrial center in the transitional area between the valley of the Ob River and the Salair Ridge, the Southwestern Siberia, Russia.

At the first stage, DTM of the city and its environs was made using *GIS Karta* (ZAO KB Panorama, Russia). The DTM construction made it possible to obtain derivative relief models and conduct spatial analysis. The hypsometric mapping of the relief is shown in Fig. 3a.

The morpho-isographs were outlined to mark the natural fluxes of matter through the city. Having conducted an extended morphometric analysis of the relief, the DTM-based derived models of the gradient and the exposure of slopes with horizontal and vertical curvature were constructed (Fig. 3b). There were distinguished a dispersion zone, where the dispersion of matter prevailed over the accumulation; an accumulation zone, where the accumulation of pollutants prevailed; and a transit zone, which occupied an intermediate position between the other two zones. Each parameter was represented as a separate information layer, formed according to the DTM, as shown in Fig. 3b. Then they were consistently compared to identify the landforms that contribute to the spread and accumulation of pollutants.



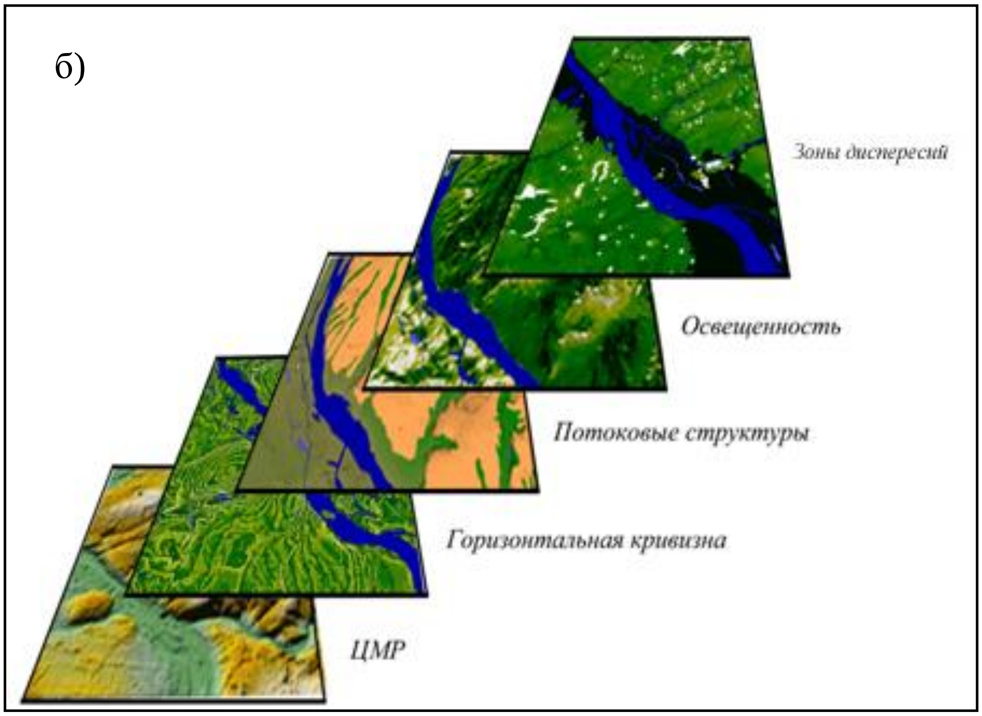


Fig. 3
Geoinformation modeling of the relief of Novosibirsk: (a) a fragment of the digital hypsometric relief map; (b) model layers for the morphometric analysis

The second stage of experiment involved collection, analysis and cartographic modeling of data on pollution of the main environmental compartments within the city. The source data were obtained from the following organizations:

- the West-Siberian Center for Hydrometeorology and Environmental Monitoring (data on the air pollution, surface water pollution, and technogenic radiation pollution),
- the State Federal Unitary Geological Enterprise ‘Urangeologorazvedka", the Siberian branch ‘Berezovgeologia’ (pollution of soils with heavy metals, natural radiation background),
- the Russian Federal Service for Surveillance on Consumer Rights Protection and Human Well-being (Rospotrebnadzor), the Department of Radiation Hygiene in Novosibirsk Region (concentration of Radon-222 in the soil air).

The cartographic analysis and environmental situation modeling produced a series of industry-specific and composite digital maps[14]. A fragment of the composite environmental map of Novosibirsk and the associated database is shown in Fig. 4.

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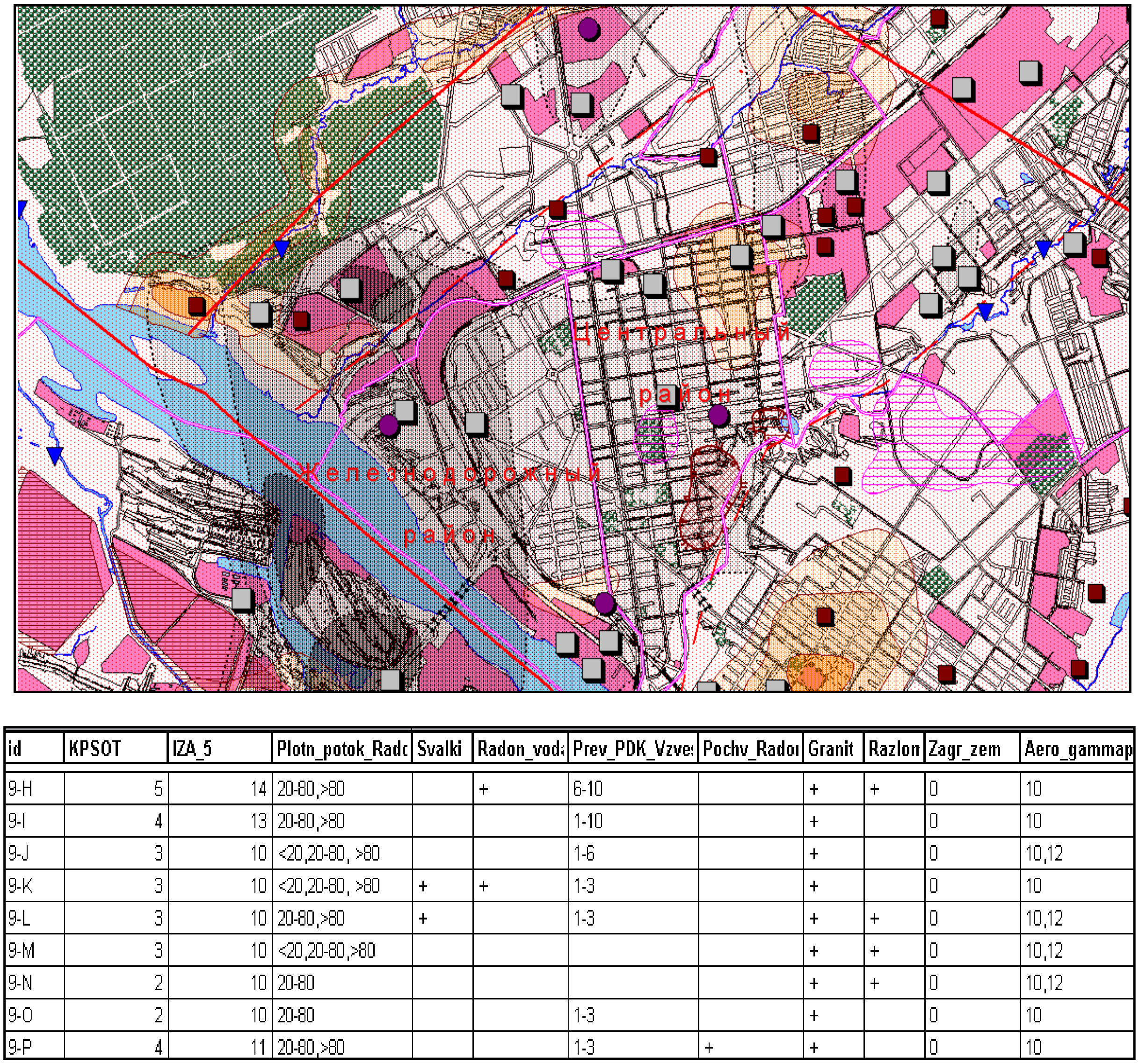
[14] S. S. Dyshlyuk; L. A. Romashova & O. N. Nikolaeva, “On the use of environmental maps in creating environmental companty spatial data infrastructure”, Geodezija i kartografija, num 4 (2016): 18–25 y Yu. V. Gavrilov; O. N. Nikolaeva & L. A. Romashova, “Experience and results of system mapping of ecological situation in Novosibirsk”, Izvestiya Vuzov “Geodesy and Aerophotography”, num 3 (2011): 91–94.



id	KPSOT	IZA_5	Plotn_potok_Rad	Svalki	Radon_vod	Prev_PDK_Vzve	Pochv_Rado	Granit	Razlon	Zagr_zem	Aero_gammap
9-H	5	14	20-80,>80		+	6-10		+	+	0	10
9-I	4	13	20-80,>80			1-10		+		0	10
9-J	3	10	<20,20-80, >80			1-6		+		0	10,12
9-K	3	10	<20,20-80, >80	+	+	1-3		+		0	10
9-L	3	10	20-80,>80	+		1-3		+	+	0	10,12
9-M	3	10	<20,20-80,>80					+	+	0	10,12
9-N	2	10	20-80					+	+	0	10,12
9-O	2	10	20-80			1-3		+		0	10
9-P	4	11	20-80,>80			1-3	+	+		0	10

Fig. 4
Compilation of data on environmental pollution

Systematized and presented on one general geographic foundation, the data enabled the environmental zoning of the city. The territory within the administrative boundaries of Novosibirsk was divided into 1×1 km cells, and the comprehensive ecological status indicator was calculated for each of them (see KPSOT column field in Figure 4). The zoning was carried out in accordance with ‘Criteria for assessing the environmental situation in the territories for identifying zones of emergency ecological status and zones of ecological disaster’, which is a methodology approved by the Russian Ministry of Natural Resources. Fig. 5 shows the results of zoning[15].

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[15] O. N. Nikolaeva; L. A. Romashova & O. A. Volkova, “Ecological maps application for environment monitoring”, Interexpo Geo-Siberia, num 1(2) (2013): 9–13.

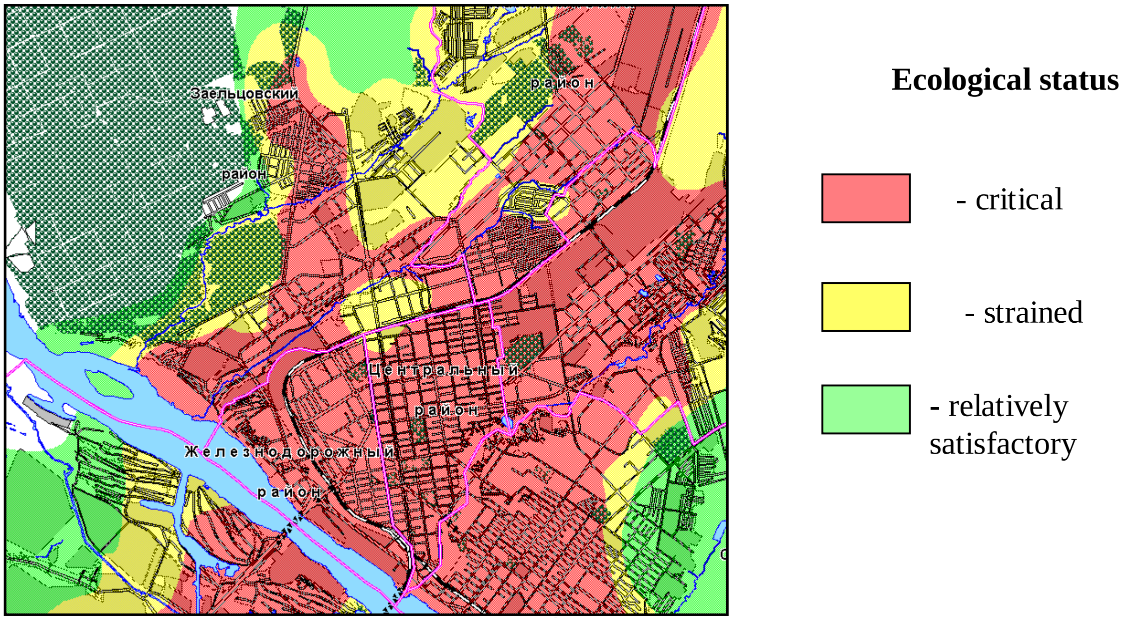

Fig. 5
Cartographic visualization of ecological zoning in Novosibirsk (a fragment)

The conducted mapping allowed forming a reliable and detailed understanding of natural and anthropogenic fluxes of pollutants in the city and analyzing the location of environmentally hazardous technogenic objects. Industrial facilities on the right bank of the Ob River were considered as examples of such objects.

A comparison was made between the locations of environmental risk zones, established in the course of ecological zoning without taking into account the impact of the relief, and the distribution of natural fluxes (Fig. 6).

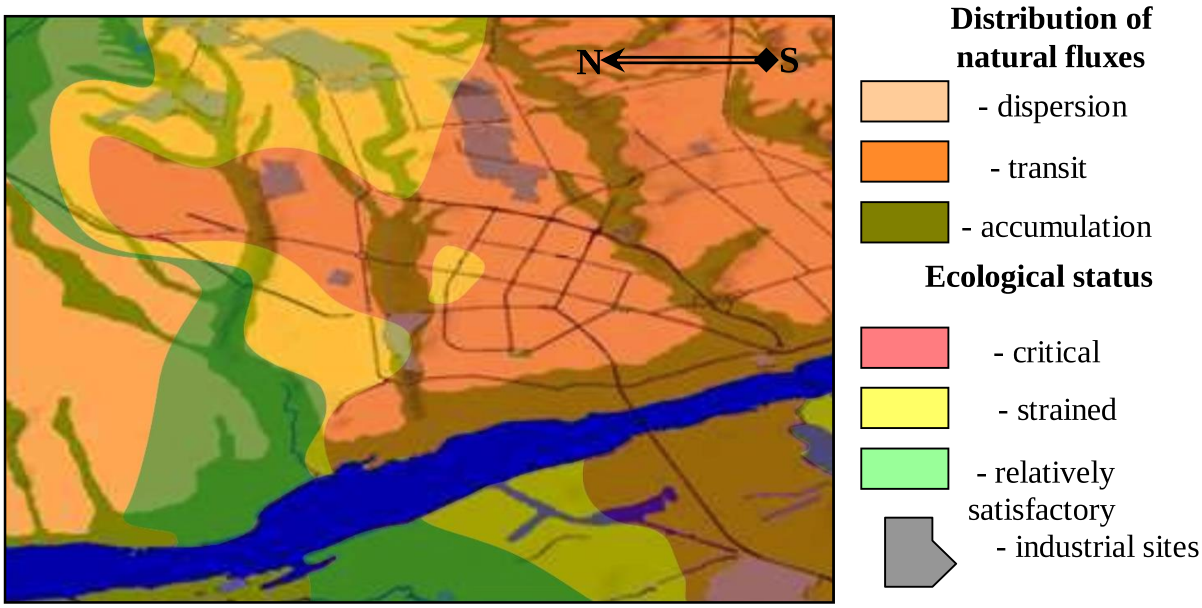

Fig. 6
Integrated mapping of ecological risk zones and distribution of natural fluxes

The performed overlay analysis identified the areas with predominating transit and accumulation zones where pollutants concentrate. Additional fieldwork was carried out within these areas to collect samples from the environmental compartments for analysis. There were studied three compartments where distribution of pollutants is most dependent on the morphometric parameters: ground level air, surface soil, and surface waters (from three small rivers – Kamenka, Yeltsovka-1 and Yeltsovka-2). In accordance with the current program of observations of the West-Siberian Center for Hydrometeorology and Environmental Monitoring, the following indicators were determined and compared to the regulatory limits:

- concentration of five priority pollutants in the ground level air;
- concentration of six priority pollutants in the surface waters of small rivers within the city;
- concentration of thirteen heavy metals and arsenic in the soil.

Also, the air pollution index, the air pollution index, specific combinatorial index of surface water pollution, composite index of soil contamination with heavy metals and the composite index of soil contamination with heavy metals were recalculated on the basis of the new data.

The fieldwork findings allowed revising the previously determined values of the comprehensive ecological status indicator and to correct the boundaries of ecological risk zones, taking into account the impact of the relief on the transport of pollutants. The performed studies confirmed the hypothesis that pollutant concentrations increase in the accumulation zone and decrease at the watersheds. In the case of Novosibirsk, the accumulation zones are the valleys of the small rivers Kamenka, Yeltsovka-1 and Yeltsovka-2 and the floodplain of the Ob River (Fig. 7).

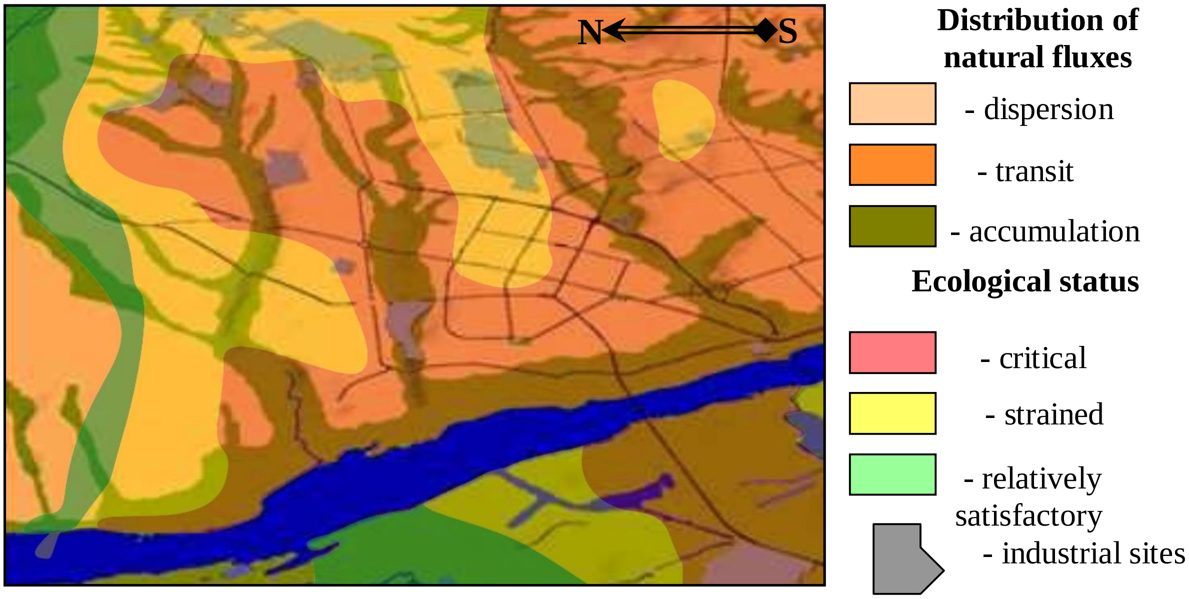

Fig. 7
Results of the ecological status assessment taking into account the natural fluxes of pollutants

In sum, the created 3D-models enabled to establish the territory-related patterns of pollutant distribution and to identify the zones of pollutant dispersion, transit and accumulation. Such information appears important for recording the spread of technogenic pollution. However, it should be noted that in some cases, deviations from the established patterns were observed; this can be attributed to various natural and anthropogenic factors (wind rose, water permeability of soils, covering of the geological substrate).

Conclusion

Each urban territory features specific natural conditions, man-made infrastructure and sources of pollution. The proposed approach to ecological status assessment of territories is based on the spatial analysis of premises that affect the distribution of pollutants. The premises arise from the natural conditions, among which the relief features play the determining role. The morphometric analysis of the relief, performed using modern GIS, provides a variety of data on the spatial distribution of pollutants. The knowledge of the relationship between the natural and anthropogenic fluxes of pollutants and the level of pollution of the territory contributes to the improvement of the instrumental monitoring. With such data in hand, the stationary posts for environmental monitoring, the key areas and the sampling points can be placed correctly within the monitored territory.

Geoinformation analysis and cartographic 3D modeling of the natural and anthropogenic fluxes on the urban territory provide for a systematic overview of the environmental situation in the city and enables ecological status assessment within a cell with a varying degree of detail.

The possibilities of geoinformation technologies in the field of 3D visualization improve the reliability of the research, simplify the interpretation of results and visualize the relationship between natural processes and anthropogenic activities with sufficient clarity.

The relief is a factor determining the processes of distribution of pollutants. Therefore, the integrated methods of relief data analysis contribute into the objectivity of the ecological status assessment. Hence the functional zoning of urban territories can be rationalized and the actions, aimed at the protection environment and public health, can be planned more efficiently.

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