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INTEGRATED ASSESSMENT AND GIS-MAPPING OF THE ENVIRONMENTAL STATE OF THE CITY OF VORONEZH (RUSSIA)

ABSTRACT. The authors have created a geoinformation-analytical system (GIS) for integrated assessment and mapping of the ecological conditions of the territory according to the criteria of anthropogenic impact and quality of the urban environment, as well as the response of woody plants and the health of the child population (on the example of Voronezh – the largest industrial city of the Central Chernozem region).

It has been identified that anthropogenic pollution is formed by the industrial-transport sector and varies with regard to the features of the functional planning infrastructure; near the industrial facilities of the petrochemical profile in the left-Bank sector of the city, conditions for the existence of woody plants significantly worsen, which is manifested in the inhibition of their development; child morbidity rate is significantly higher in industrially polluted neighborhoods with high load of pollutant emissions from industry and transport. The diseases primarily associated with pollution are congenital anomalies, neoplasms, endocrine pathology and diseases of the urogenital area.

The industrial zone is the main contributor to the total pollution of air, but the transport zone is the main contributor to the total pollution of soil and snow cover.

KEY WORDS: geographical information system, industrial pollution, health of the population, environmental assessment, Voronezh.

INTRODUCTION

Modern large cities are the centers of the most acute ecological problems. The monitoring and mapping of the ecological status of the urban environment are important tools of spatial planning and environmental safety and contribute significantly to solution of the contemporary urbanization problems.

At the turn of XX–XXI centuries, increasing density of urban development in large industrialized cities and the increase of air and soil pollution contributed to the decline of the quality of the urban environment. This is manifested in a certain environmental response – the inhibition of development of woody plants. Morbidity of the population has also increased.

Research in the field urban ecology and environmental geochemistry of urban landscapes in combination with the concept of environmental risk supports the relevance

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of quantitative evaluation of correlations "dose-effect" for a wide range of factors that shape the ecological situation and public health in large cities.

Theoretical approaches to the study of this problem have been discussed in numerous works of national and foreign scientists in the field of urban ecology, ecological geochemistry and medical geography [Bezuglaya et al., 1991; Ekogeokhimiya gorodskikh…, 1995; Kasimov et al., 2013; Malkhazova et al., 2011, 2014; Revich, 2010]. This allowed justification of risk-based modern approach to the problem of "environment - health," focused on the identification and quantitative estimation of environmental risk factors, as well as on minimization of their negative impact on the biota and population.

These problems are relevant for many large industrial centers of Russia, including the city of Voronezh. Earlier, a number of analytical studies on the environmental zoning of urban environment and risk assessment for public health from adverse environmental factors on the territory of Voronezh city was conducted [Kurolap, Klepikov et al., 2006, 2010]. Methodologically these studies were based on the leading environmental risk factors, particularly, air-technogenic and soil-geochemical. However, aspects of integrated environmental assessment of linkages in the system "atmosphere – soil – biota – health of the population" remain insufficiently studied.

The aim of this work is development and testing of approaches to integrated assessment of the ecological state of the territory of a large industrial center with application of modern geoinformation technologies. Voronezh is selected as a model city because it is a major industrial town of the Central Chernozem region with a population of over 1 million people.

MATERIALS AND METHODS

The following methods were used: methods of environmental, geochemical, biological,

and GIS research and assessment of ecological risk for the health of the population. Methods of probabilistic and statistical analysis in MS EXCEL and STADIA, as well as GIS technologies in the of MapInfo Professional 9.0 environment were used as integrating instrument for a comprehensive assessment and mapping of the environmental situation of the urban environment.

We have developed an automated GIS system for ensuring environmental monitoring in the Voronezh territory ("ECOGIS Voronezh"), including the storage subsystem of the environmental-geochemical and health-geographical data, as well as program-algorithmic support of ecological risk assessment.

The main principles of creation of the specialized GIS are complex systematic organization of diverse environmental data, linking to an existing environmental control system, automatization of procedures of data analysis and calculation of environmental risks, and the potential of timely GIS-based mapping.

The source data for creating of "ECOGIS Voronezh" were obtained during experimental research by the authors and provided by the regional ecological and monitoring agencies of the city. The structure of the GIS is shown in Fig. 1.

The 5-year period (2009–2013) was selected as a basic time period for assessment of the quality of the urban environment. Three levels of information generalization were defined as operational territorial units (OTU): 1) functional planning city zones (6 zones and the backgraund, altogether 7 territorial units); 2) areas of service children's clinics in the city (12 areas); 3) special points of monitoring of the state of the urban environment (75 points, including fixed and mobile control posts of the air system of the hydrometeorological service, the sanitary-epidemiological service, and, additionally, the selected monitoring points for uniform coverage of the territory of the city environmental management system).

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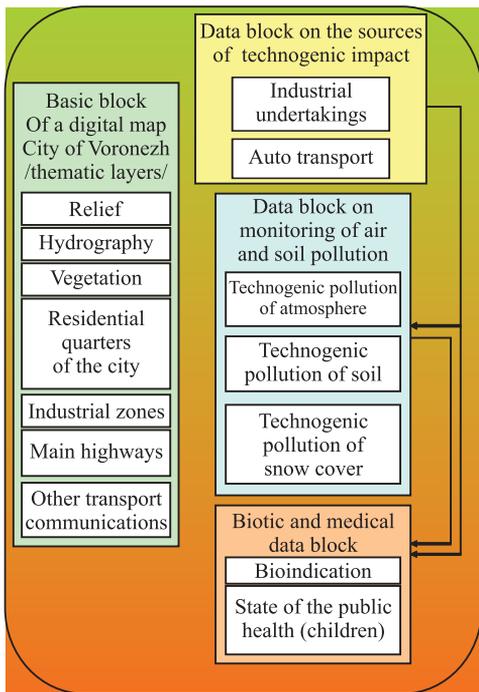
Fig. 1. The structure of the database for the integrated environmental assessment of the urban environment state.

Analysis of the formation of zones of technogenic pollution of the urban environment was conducted in several main directions: 1) influence of seasonal factors and dispersion of pollutants on the concentrations of pollutants in the atmosphere; 2) estimation of the statistical influence of the characteristics of industrial and transport load on concentrations of pollutants in the atmosphere, snow, and soil; 3) analysis of the correlation between pollution of soil and pollution of snow cover by comparing the pollution of these environments based on the most representative items of environmental monitoring.

All the objects on a digital map of Voronezh differentiated into the following basic thematic layers: 1) vegetation (intra-city and suburbs-native green areas, parks, squares, forming a "green frame" of the urban agglomeration); 2) hydrography (Voronezh reservoir, permanent and temporary watercourses); 3) residential

blocks (divided into 3 functional sub-zones: "CH" – the Central historical part of the city, including multi-storied public-business development and "old" 5-storey building of the 1950s–1970s; "MD" – neighborhoods with modern high-rise buildings mostly from 9 floors and higher constructed in the 1980s – the beginning of this century; "PS"– the "private sector": predominantly low-rise and cottage resedential construction); 4) "Ind" – industrial zones (area occupied by industrial enterprises and their sanitary-protection zones); 5) "Tr" – traffic areas, including main automobile highways (and major traffic streets); 6) "R" – the recreational-residential zone covering the urban area and suburban "bedroom" micro-districts. Suburban territories outside of urban areas are selected as the background ("B").

The registry of 351 sources of technogenic pollution of the urban environment (199 industrial facilities and 152 transportation structures) with the characteristics of parameters of their impact (emissions of pollutants into the atmosphere, the intensity of traffic) was created to assess the impact of industry and transport on the urban environment; these data were "attached" to the spatial data.

Using the programming language MapBasic, the process of risk assessment for public health associated with chemical air pollution was automated. Was designed a special software module that implements calculations of quantitative risk levels for health in accordance with hygienic approaches [Onishchenko, Rachmaninov et al., 2002]. Formulas (1) and (2) were applied for calculating the levels of risk.

Carcinogenic risk (CR) in the course of life was determined by the formula (1):

$$CR = ADD * SF \qquad (1)$$

where ADD is average daily dose in the course of a lifetime, mg/(kg*day); SF – carcinogenic potential factor.

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Non-carcinogenic risk (for air pollution) was quantitatively evaluated by calculating the hazard ratio *(HQ)* by the formula (2):

$$HQ = Ci/RfC \qquad (2)$$

where HQ is the hazard ratio; Ci – average concentration (mg/m^3); RfC – reference (safe) concentration (mg/m^3).

Based on the created registry of industrial and motor vehicle contributors to the pollution of the atmosphere, an original technique for hazard assessment of the impact of sources of air pollution was developed. This technique includes a gradual implementation of the following calculation procedures (1)–(4).

1. Assessment of the potential hazard of industrial contribution. For each industrial facility (industrial site), the hazard indexes of emissions of polluting substances were calculated. The hazard classes of substances were taken into account. The weighted average index of ecological danger of the enterprise was determined similarly to the approach in [K.A. Bushueva, 1979], used to calculate the total air pollution index – K_{atm}, according to the formula (3):

$$K_{Atm} = \left(\frac{C_1}{N_1 MPC_{C_1}} + \frac{C_2}{N_2 MPC_{C_2}} + ... + \frac{C_n}{N_n MPC_{Cn}} \right) t, \qquad (3)$$

where C_i is the average annual concentration of i-substance; MPC_i – average daily maximum permissible concentration of i-substance; N_i is a constant that takes values 1; 1,5; 2; 4 respectively for substances 1, 2, 3, 4 hazard classes; t = P/P$_o$, where P – average annual percentage frequency of calms, %; R_o = 12.5 percent.

Using weight constants, the following formula was applied (4):

$$I_{ind} = \frac{I_{1cl}}{N_1} + \frac{I_{2cl}}{N_2} + \frac{I_{3cl}}{N_3} + \frac{I_{4cl}}{N_4}. \qquad (4)$$

Separately was determined the risk index of emissions of carcinogenic pollutants (CR) – total emissions of substances with an established carcinogenic effect in % of citywide emissions (I_{CR}). The carcinogens considered were the emission of carcinogenic substances belonging to groups 1, 2A and 2B according to the IARC classification given in [Onishchenko G.G., Rakhmanin et al., 2002].

2. Evaluation of potential hazards of motor vehicle contribution. First, the average intensity of movement of vehicles for each of the main streets the city was determined taking into account their category [Yakushev et al., 2013]. Further, according to the Directory of the streets, indices of the potential danger of emissions from motor vehicles were determined: index of the potential danger of emissions from passenger vehicles /I_{lgc}/ – they are the ranking indicators according to the traffic flow of vehicles through the streets of various categories; similarly, for trucks /I_{grs}/, buses /I_{awt}/, and the total grade of vehicle load by the total intensity of vehicles on the street of a given category /I_{atn}/.

3. Calculation of the total index of environmental burden of industrial and transport infrastructure (I_Σ) on the urban environment for any operational territorial unit is based on weighting the importance of the three main indicators of risk of emissions of pollutants from stationary and mobile sources of air pollution (for example, in the service area of the pediatric clinic) by the formula (5):

$$I_\Sigma = \sum_{i=1}^{n} \left(I_{ind} + I_{CR} + I_{atn} \right), \qquad (5)$$

where i...n is the number of objects (industrial areas, street slopes) within a given territorial unit.

4. Creation of digital maps of hazard of technogenic impact on the urban environment. It is performed by spatial interpolation of values of indices of

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environmental risk of industrial and motor vehicle contributors by the method of isolines. As a result, we calculated **areal rates** of emission of pollutants and the intensity of traffic through the residential areas of the city (example of the spatial distribution of the emission load is presented in Fig. 2).

To assess the response of biota to industrial pollution we have used special bioindicative research methods. The most abundant

species of woody plants-bioindicators were selected: birch (*Betula pendula Roth*.) and Lombardy poplar (*Populus pyramidalis Borkh*.). This analysis of the leaves samples following the accepted techniques for analysis of fluctuating asymmetry of leaf plates made it possible to calculate the integrated indicator of stability of development. Various morphometric parameters of the lamina of these species in different functional zones of the city were evaluated as biological criteria.
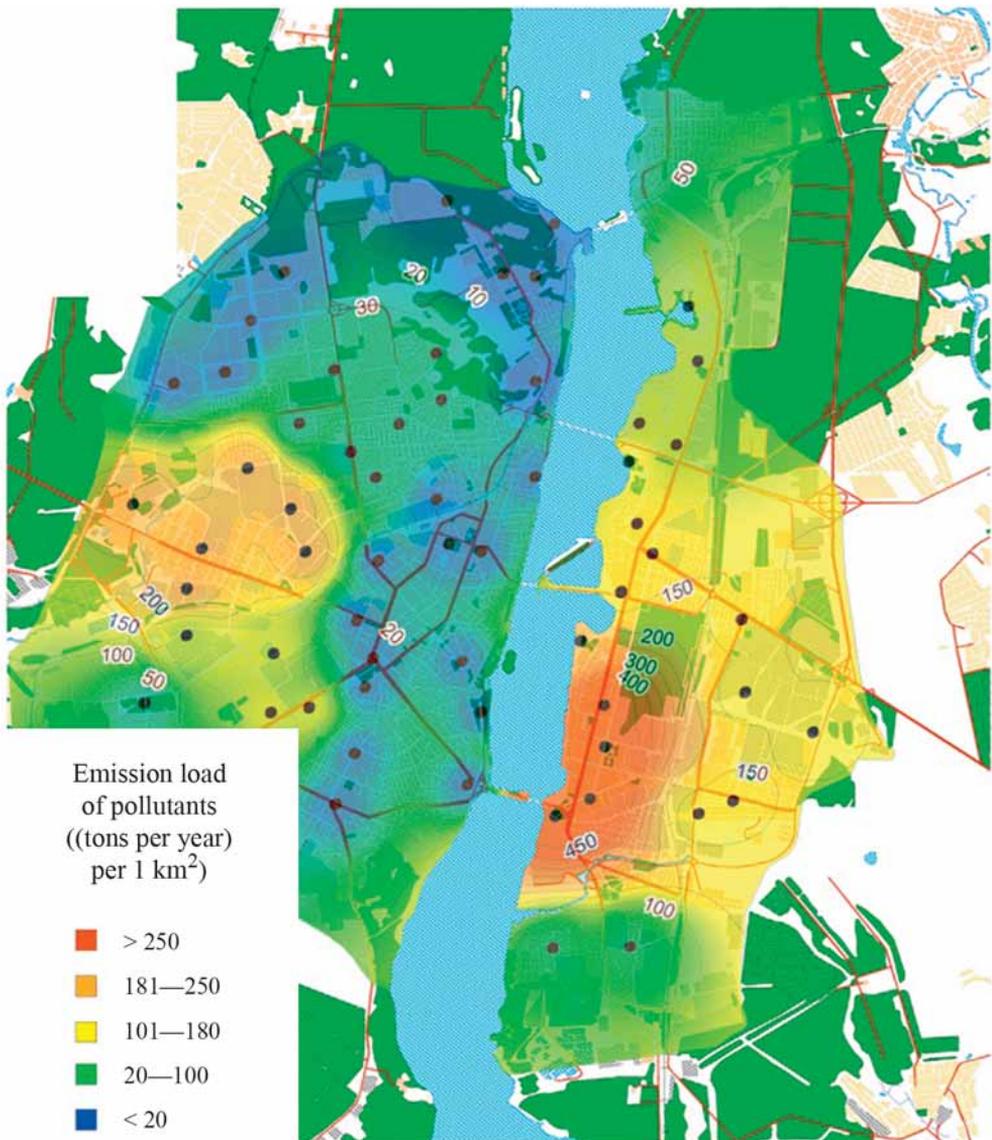

Emission load
of pollutants
((tons per year)
per 1 km²)

- ■ > 250
- ■ 181—250
- ■ 101—180
- ■ 20—100
- ■ < 20

Fig. 2. The index of the total emission load of pollutants from stationary sources (tons per year per 1 km²).

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The analysis of internal interactions in the system "atmosphere – snow – soil – biota – population health," as well as the evaluation of the dependence of child morbidity on the parameters of technogenic pollution of the urban environment were based on the standard correlation and regression analysis with coverage of data on the territorial polyclinics of the city and on formal territorial interpolation for specially allocated items of monitoring of the urban environment.

RESULTS AND DISCUSSION

The analysis of correlations in the system "sources – pollution – transit environment – sequestering abiotic environment" has shown, in general, a logical pattern: in the total number of correlations, significant positive coefficients dominate (mostly in 55–84 % of cases for the majority of the criteria). The most stable relationships are marked by the most massive emissions of substances 3 and

4 classes of hazard, carcinogens, as well as the intensity of the total industrial traffic load, determined largely by passenger vehicles and the contribution of carcinogens, which present in the emissions from stationary sources. A fragment of the most typical links is shown in Table. 1.

A ranking of the reverse "response" of geochemical indicators on the industrial traffic impact showed stronger response criteria for the quality of atmosphere and soil and lesser for snow. The priority geochemical indicators include: carbon black and formaldehyde in the atmosphere, nitrogen compounds in snow, the total index of soil contamination by mobile forms of heavy metals – lead, zinc, copper, and cadmium.

The most polluted are the industrial and transport areas, and between the integral indicators of atmospheric pollution and soil there is a proved positive correlation,

Table 1. Generalized indicators of the stability of correlations between the parameters of the impact of industrial traffic loads and indices of air, snow and soil pollution

| Impact criteria (P_i)		"Response" criteria	
Designation	Impact rate *	Ecological and geochemical criteria	Correlation coefficients P_i **
Index of integral industrial and transport load (I_Σ)	84.2 %	the atmosphere (formaldehyde)	0.39
		the atmosphere (carbon black)	0.51
		the atmosphere (K_{atm})	0.38
		snow (NO_3^-)	0.41
		snow (Pb^{2+})	0.32
		soil (Pb)	0.44
		soil (Cd)	0.65
		soil (pH)	0.45
		soil (AIP)	0.49
The ratio of total vehicle load (T_{aTH})	60.5 %	the atmosphere (carbon black)	0.43
		snow (pH)	0.68
		snow (mineralization)	0.54
		snow (Cl^-)	0.51
		snow (NH_4^+)	0.66
		snow (NO_3^-)	0.44
		soil (benzopyrene)	0.63

*) The proportion of positive significant correlations
**) Statistically significant correlation coefficients (r) > 0.56.

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indicating a significant dependence of the aerogenic pollution of the soil by the inflow of pollutants (r = 0,77).

Conducted bioindicative studies based on the technique [Zakharov, Clark, 1993] using a scale to evaluate the favorability of species growing conditions showed that the zones with adverse conditions are located near industrial plants and major transport routes, which is most clearly manifested in the left-Bank sector of the city, near JSC "Voronezhsintezkauchuk" and CHP-1. The safest indicators of environmental quality are found in the recreation area and the residential district of the private sector. Most of the city's territory has the average level of deviations from conventional norms, which is a moderate degree of anthropogenic pollution of the urban environment.

The correlation of biological indices for functional planning zones is shown in Fig. 3. In general, the deviation of the integral index of stability of development from the physiological norm is higher in the left-bank part of the city. This is due to the concentration there of many industrial objects, and also to features of low-lying terrain, which are not conducive to purification of the atmosphere.
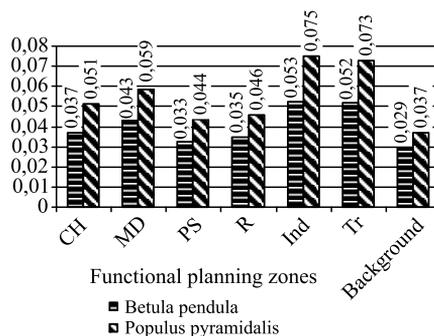
Fig. 3. The integrated indicator of stability of development of silver birch (*Betula pendula*) and poplar (*Populus pyramidalis*).

Selective statistical analysis of bioindicative features supported the conclusion that the data on the quality of the environment, obtained by calculating fluctuating asymmetry, are generally consistent with available information on the concentrations of various pollutants in ambient air, as well as with the layout of the main industrial pollution sources of the urban environment.

Quantitative assessment of the impact of industrial traffic pressure criteria and of the environmental and geochemical indicators of the quality of the atmosphere, snow and soil showed prevalence of positive correlations (about 60 % of cases), confirming the

**Table 2. The main geochemical criteria of the ecological state
of the functional and planning areas of Voronezh**

Functional planning zones	Atmosphere (substances – mg/m^3)				Snow			Soil	
	Sulfur oxide IV	Formal-dehyde	Phenol	K$_{atm}$	pH	Mineraliza-tion, (mg/l)	NO$_3^-$ (mg/l)	Lead (mg/kg)	AIP*
Residential (MD)	0.071	0.037	0.072	0.48	6.03	123.9	8.10	2.26	29.8
Residential (CH)	0.050	0.069	0.101	0.66	6.27	109.5	8.69	2.99	23.4
Residential (PS)	0.081	0.083	0.071	0.55	5.72	112.9	3.25	2.71	18.0
Industrial (Ind)	0.138	0.179	0.251	1.05	6.11	135.0	9.73	2.45	52.9
Transport (Tr)	0.144	0.181	0.202	0.97	6.55	143.5	17.30	3.92	66.0
Residential-Recreational (R)	0.036	0.014	0.032	0.31	5.74	116.0	5.80	2.02	12.2
Background	0.028	0.007	0.029	0.26	5.39	104.5	1.56	2.00	16.1

*) AIP – the aggregate index of soil pollution with heavy metals

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increase in morbidity of children living in technogenically-loaded areas.

The priority health risk factors (for common weight positive significant correlations) are: the ratio of the emission load of carcinogenic substances, especially, the indices of road congestion. In such areas, children have generally higher levels of morbidity for several diseases (congenital anomalies, neoplasms, endocrine pathology and diseases of the urogenital area). The majority of correlations are reliable.

The indicator parameters of chemical pollution of snow cover that reflect general industrial and transport pollution include the total dissolved solids, nitrogen compounds, chloride ions and the presence of lead in the melting snow.

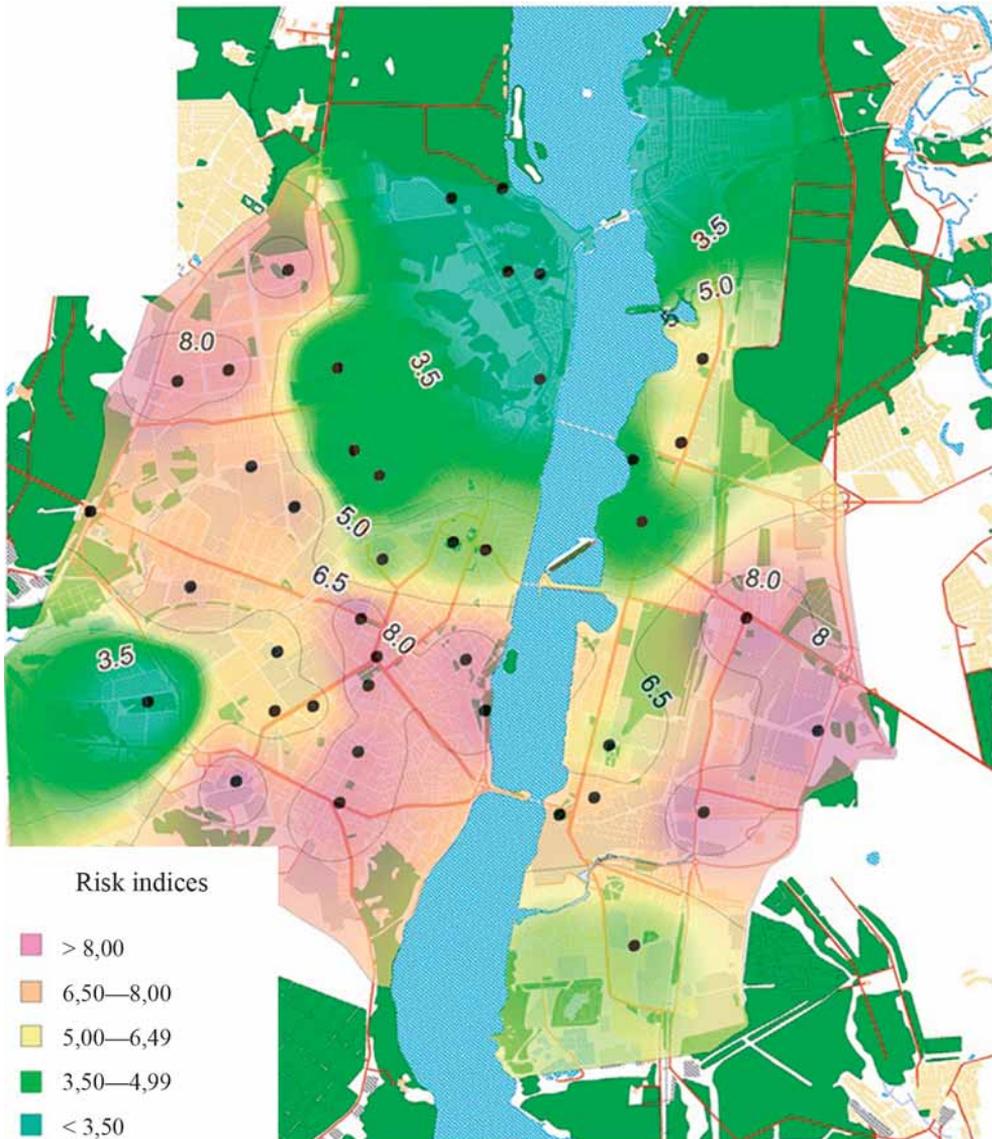A multifactorial model (formula (6)) was built based on the priority risk factors; the model

Fig. 4. Integrated assessment of the ecological condition of the territory of the city of Voronezh (method IDW interpolation).

reflects the total effect of the 5 risk factors on the overall morbidity rate of the children population (multiple correlation R = + 0.82):

$$Y = -88.34 - 25.18(X1) + 0.0037(X2) +$$

$$+ 545.59(X3) + 4.70 (X4) + 8.93 (X5), \qquad (6)$$

where $X1 - (P_{CR})$ – coefficient of emission levels of carcinogens (t/year per 1 km^2); $X2 - (T_{atn})$ – the total traffic intensity of vehicles (auto/h per 1 km^2); X3 – is the comprehensive index of atmospheric pollution (K_{atm}); X4 is the total mineralization of snow cover (mg/l); X5 – the total index of soil pollution with heavy metals (SDRs).

To increase the validity of zoning, we applied methods of multivariate statistical analysis. In particular, the use of cluster analysis has led to a more accurate classification of functional-planning areas according to the similarity of the nature of environmental pollution and feedback of living organisms. Three cluster groups were isolated: a) industrial and transportation zones together (the most technogenic polluted); b) residential, including all the sub-zones regardless of the number of floors and historical-compositional construction (areas of moderate contamination); c) residential recreation and the background (the most environmentally safe, comfortable).

The main geochemical criteria of the ecological state of the urban environment are shown in Table 2. We have calculated the integral evaluation score based on set of particular indicators of the ecological state of the urban environment and children health. This score was obtained by calculating a weighted average of scores characterizing the degree of medico-ecological tension of the area.

The final element of the integrated assessment was the creation of a map which shows gradient differences of environmental risk indices. The data was processed in respect to 46 of the most representative monitoring points (Fig. 4). The compiled map illustrates spatial differences,

of up to about three-fold level, in risk indexes in affluent suburban neighborhoods and the community center, as well as the industrial and transportation areas of the city.

CONCLUSION

The conducted research allows us to formulate several basic conclusions: 1) industrial pollution is formed by industrial-transport sector and functional planning of the city infrastructure; 2) quality criteria for soil and atmosphere give a stronger response to industrial and traffic impacts; snow is a geochemical indicator with a significantly smaller effect; 3) near industrial petrochemical enterprises in the left-Bank sector of the city, conditions for the existence of woody plants are significantly worse. This is manifested in the deviation from the background of the indicator of stability of development of silver birch and poplar; 4) there is a statistically valid increase in the incidence of children diseases in the areas of technogenic load. Diseases with the greatest environmental dependence include congenital anomalies, neoplasms, endocrine pathology and diseases of the urogenital sphere; 5) the priority health risk factors – the ratio of the emission load of carcinogens and indices of road congestion; 6) the territory of Voronezh industrial zone "leads" in the total pollution, while transport "leads" in the total pollution of soil and snow cover.

The identified trends may be useful for regional environmental and hygienic services for the development of targeted environmental monitoring programs and may reduce the risk of ecologically caused diseases of the population in the conditions of intensive technogenic pollution of the urban environment. In particular, there is a need for a targeted environmental policy to reduce environmental risk and to improve the urban environment of Voronezh. Its components may include the following: reconstruction of transport networks by increasing their width and the

average speed of movement of vehicles and enhancing quality of road surface; creation of "transport corridors" similar to "organic systems" of urban transportation in many European cities; change in the fuel balance of the thermal power generation industry with a complete transition to gas as fuel; larger green urban space with the introduction of pollution resistant green plantings and a more widespread use of "vertical gardening" of walls and roofs, based on the experience of several major cities in Europe, which will reduce air pollution near the highways.

ACKNOWLEDGEMENT

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