Geoinformation Landscape-Geochemical Mapping of Urban Areas (with the Example of Eastern Administrative District of Moscow)

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***Abstract*-The methodological approaches to compilation of landscape-geochemical maps of urban areas have been developed around a cartographic database which systematizes digital maps presenting the land-use zoning of a study area, its landscape structure and anthropogenic anomalies of heavy metals. The methods have been tested in the course of geoinformation landscape-geochemical mapping the Eastern Administrative District of Moscow. A landscape-geochemical map has been compiled displaying the taxonomy of urban landscapes with respect to factors of heavy metal accumulation and contamination levels of snow and soil cover.**

Keywords- Geoinformation Mapping; GIS; Geochemistry of Landscapes; Urban Area; Contamination; Risk Assessment; Moscow

I. INTRODUCTION

The modern city is a particular human environment, the most important element of which is natural landscapes and their components, as well as man-made landscapes, more or less modified in the process of urbanization. That's why urban landscapes require special methodological approaches and techniques for their study and mapping.

Theoretical and methodological basis of landscape-geochemical mapping of the cities constitutes landscape geochemistry and applied environmental geochemistry [1, 2]. They are found on the concept of B.B. Polynov about geochemical relationships between the landscape components, which are carried out by migration fluxes of chemical elements. Areas of the earth surface with a certain type of elements migration were called geochemical landscapes [3]. Landscape maps of urban areas rests on studies of individual components of the urban environment. In Russia, they are usually presented by maps of native landscapes, obtained by field observations and pale reconstructions of original natural structure [4-9]. These maps are important for assessing the state of the environment, since they reflect inherited behavior features of chemicals in the modern urban landscape.

However, the current processes in landscapes are still more significantly affected by anthropogenic factors defined by type of land use. Maps of land-use zoning are required for urban research and designing, as well as for environmental monitoring. In the first case maps characterize the city territory depending on types of its current or intended use [10, 11]. For environmental monitoring subzone of natural recreational areas representing ecological frame of urban area are allocated [12-18]. The urban area itself is often considered as a three-dimensional space, where buildings with varying heights exist; mapping units are selected according to both urban designing borders and orohydrographic boundaries [19, 20]. Some experts in urban ecology considered it necessary to show a combination of environmentally negatives (industrial plants, oil fields, garages, parking lots, etc.), neutral (residential blocks) and positive (parks, planting, agricultural land, etc.) areas of the city [21].

Mapping pollution of urban landscapes components involves the consideration for not only the complex of anthropogenic factors but also landscape factors, as sites of pollutants accumulation are determined by sources of emissions and the existing features of urban nature as well [2, 22-26]. Basic principles of large-scale geochemical mapping of landscapes modified by anthropogenic activities were formulated in [27]. The Russian experience of large-scale landscape-geochemical mapping urban areas is small [4, 21, 28, 29], and its technique is rather complicated and not fully developed [28, 30]. Rapid development of geoinformation methods and technologies based on geographic information systems (GIS) has opened up new possibilities for compilation of landscape-geochemical maps of cities and allows the benefits of a systematic approach to the analysis of various data on urban landscape structure and land use [21, 31-39].

Large amounts of data on components of urban landscapes are accumulated during research. These data require ordered and systematic organization to improve efficient usability of information. In addition, there is a demand for information in the form of cartographic coverage, because maps provide the most complete spatial characterization of the study objects. Such cartographic support involves a cartographic database (CDB) containing a set of interrelated spatial data organized on certain rules and similar principles.

The objectives of the study presented herein included:

1) Geoinformation mapping of megalopolis landscapes by systematization of the data on the landscape and land-use

structure in the CDB.

2) On the basis of the designed CDB, developing and testing methods for compilation of landscape-geochemical maps that display the taxonomy of urban landscapes with respect to high-priority pollutant migration and accumulation and defining the environmental risk of landscape pollution in the various land-use zones of the city.

The Eastern Administrative District (EAD) of Moscow has a number of large industrial zones and highways, local district heating station, waste incinerator plant and several other pollution sources and for this reason was chosen as the object of the study. Heavy metals (HMs) are among the most serious pollutants, because many of them are considered to be highly toxic.

Research on HMs in soils, snow and vegetation in the EAD area has been conducted since 1989, enabling evaluation of the long-term dynamics and spatial structure of pollution in the landscape components [28, 40-44]. The results of the research provided the basis for the present study.

II. THE STRUCTURE OF A CDB FOR LANDSCAPE-GEOCHEMICAL STUDIES

Digital maps form the content of CDB, therefore, it is important to determine the structure of attribute tables based on the types of both spatial (vector, vector-topological, raster) and graphic characteristics of objects [45]. As a preliminary stage, it is necessary to develop the structure and content of the cartographic support system defining the logical structure of the CDB.

A cartographic support system was created for the Moscow EAD area. Multispectral QuickBird satellite images (2009) with a spatial resolution of 2.4 m, the Ecological Atlas of Moscow [8], cartographic and statistical Internet sources, as well as data derived from geochemical soil and snow sampling served as the main sources for mapping.

The created cartographic material consists of the following CDB blocks:

1) Basic geographic information (base maps, satellite images);

2) Maps of land-use zones;

3) Maps of the landscape structure;

4) Geochemical maps.

The digital maps were prepared according to the established principles of geoinformation mapping, including preliminary procedures for evaluating the quality of the collected data, setting up symbol systems and generalization, etc.

The rules for establishing connections among individual attribute tables are determined by a database management system (DBMS). In our case, we used the DBMS ArcGIS 9.3, which provides management capabilities to deal with cartographic information. It defines the relational data model, which allows the storage of multiparameter spatial information in the form of related tables. Relations are defined by the columns of the spatial objects' ID numbers on the map, which should be the same for all interrelated objects. This approach determines the importance of using the system of basic spatial cells for the storage of information. These cells were the land-use zones allocated within the current research project when designing the cartographic support system. Cell numbers are the same for different groups of indicators, spatially organized by land-use zones. Eventually all the blocks of information were connected and a complete logical structure of CDB was developed (Fig. 1). This structure connects the database blocks in a convenient logical model that allows joint consideration of the information to analyze and compile new maps, especially complex ones.

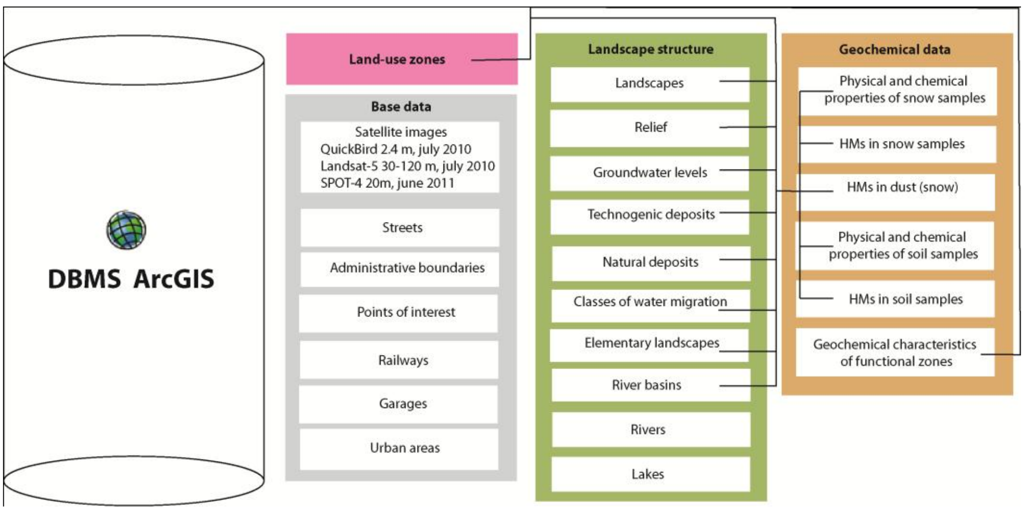


Fig. 1 The logical structure of CDB

III. THE CONTENT OF THE DATABASE BLOCKS

A. Maps of Land-use Zones

Since the type of urban land use plays a leading role in the formation of anthropogenic geochemical anomalies of pollutants [46], in our research we developed methods for land-use zone mapping and compiled a map of the EAD [43, 44]. Various statistical data, and topographic maps of cities were the main sources of information for the stored data. Updating the information to keep it adequate was expensive and time-consuming. For the same reasons, aerial photographs were not often used. Modern satellite images with spatial resolution better than 5 m, received at intervals of several days (GeoEye-1, WorldView-1, Ikonos, etc.) or even daily (RapidEye), created the conditions for the development of remote sensing-based methods for mapping urban areas [33, 34, 39].

Many urban objects (buildings, streets, highways, railroad tracks, etc.) are confidently recognized on very-high-resolution satellite images. Features and functions of objects are defined by a combination of several indicators – shape, size, color, relative position of objects, and sometimes by logical deduction. Multispectral images at a lower resolution indicate the properties of objects that are not visible on the black-and-white images.

The map of land-use zones in the EAD area of Moscow has a scale of 1:50 000 (Fig. 2). The main data sources for this map are QuickBird satellite images (Digital Globe, USA) with a 0.61 m resolution in the panchromatic band and 2.44 m in the multispectral band. The methods of automated and visual interpretation were used in the mapping. Green areas and water bodies were identified by visual interpretation on the basis of computer image classification [38], the structure of residential areas and other urban land-use zones.

The map of land-use zones serves as a basis for revealing the pollution factors and for the assessment of pollution in the study area. In the course of landscape-geochemical studies such a map helps to carry out task-oriented sampling, to identify the patterns of wind-induced transfers with respect to building locations and building clustering in residential areas. Moreover, it makes it possible to evaluate the impact of pollution sources on landscapes.

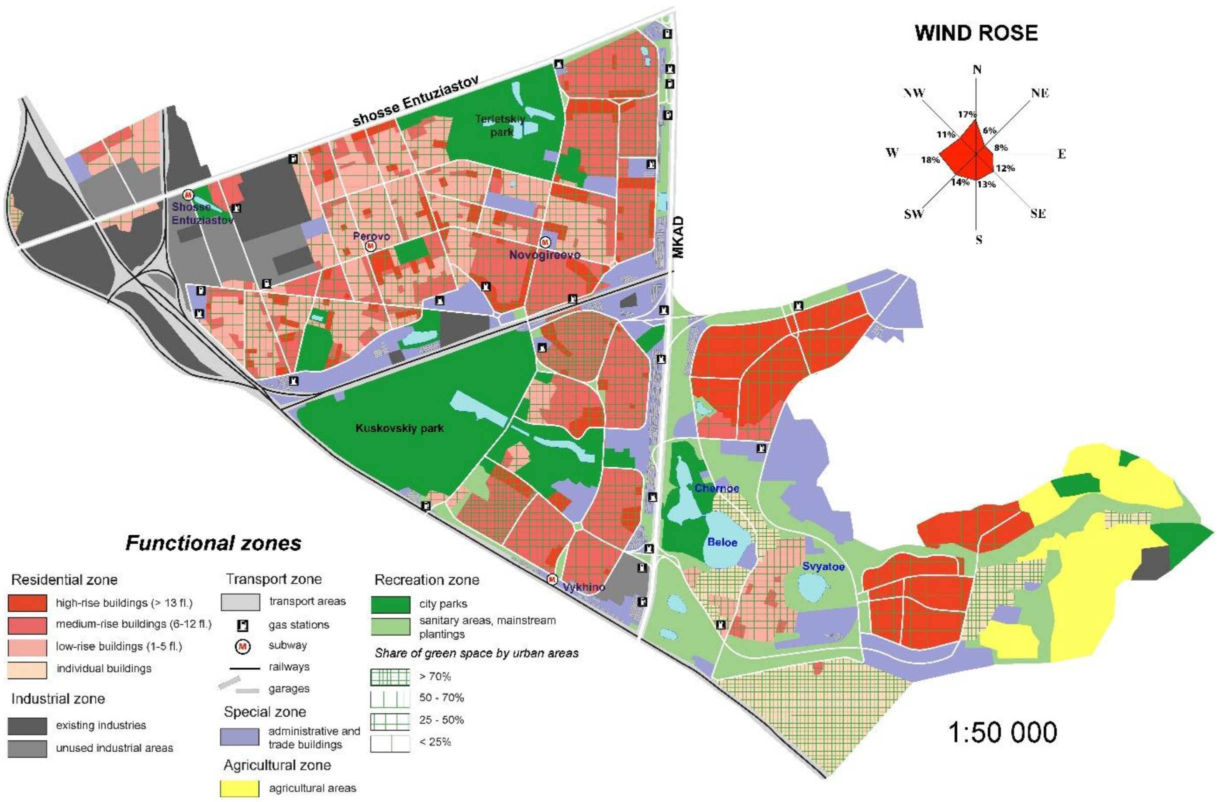


Fig. 2 The map of the land-use zones in the EAD area of Moscow [43]

B. The Maps of Landscape Structure

In the landscape-geochemical mapping of urban areas, it is important to not only display the land-use zones but also the natural conditions and their anthropogenic transformation, since these factors predict the behavior of toxicants and the dynamics of landscape pollution.

The major information on the landscape structure of the EAD was derived by analysis and assessment of geological, geomorphologic, soil, vegetation, and landscape maps from the Environmental Atlas of Moscow [8]. The maps prepared by the authors were also used (the maps of deposits, elementary geochemical landscapes, water migration classes). All these maps were presented in digital form in a separate block of the CDB devoted to landscape structure and were considered together with the application of spatial analysis – overlay, morphometric operations, geoinformation statistical analysis etc. As a result, a set of maps characterizing landscape-geochemical relationships in urban landscapes was compiled.

1) The Map of Deposits:

Quaternary deposits in the study area are overlain by anthropogenic and cultural layers. Since such layers impact the chemical composition of the soil cover and define the initial pollution levels they may contribute significantly to the environmental and geochemical status of an urban landscape. For the analysis of deposit distribution over the area of the EAD, the map displaying the taxonomy of various (natural and anthropogenic) deposits in terms of their genesis, texture and thickness was designed (Fig. 3).

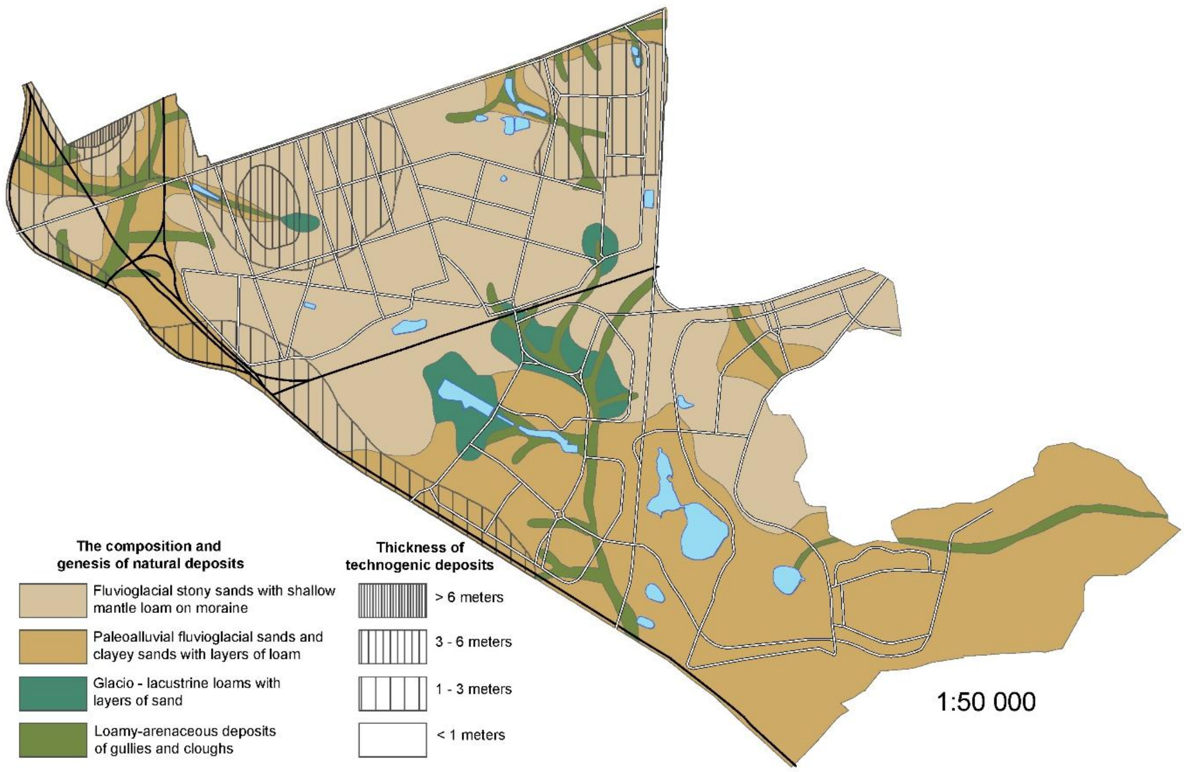


Fig. 3 The map of deposits in the EAD of Moscow

2) The Map of Elementary Geochemical Landscapes:

A map of elementary geochemical landscapes reveals catenary geochemical structure of landscapes and characterizes lateral fluxes of polluting substances in the soil cover of an urban area between interfluve positions and related depressions (Fig. 4). The geochemical classification for natural landscapes proposed by M.A. Glazovskaya was used for the map [47]. Geochemical fluxes between elementary landscapes reflect the variety of soil and slope processes and form certain paragenetic groups characterized by certain types of material, energy, as well as information exchange between subsystems. The map is a product of integrated and interrelated analysis of various maps: geomorphologic, soil, landscape, a map of soil waterlogging and others. Taking into account the boundaries of local river watersheds, five gradations (genera) of elementary landscapes have been distinguished on the map of the EAD: eluvial, transeluvial, transaccumulative, superaquatic and aquatic. Due to level relief, small elevation differences and high anthropogenic transformation of relief features, transeluvial landscapes in the EAD area are rather rare and eluvial landscapes often border superaquatic ones (Fig. 4).

3) The Map of Water Migration Classes of Chemical Elements:

The intensity of water migration of pollutants in soils and subsoils is controlled by redox conditions and reactions in solution. The combination of various redox and pH conditions produces 12 water migration classes [2]. Anthropogenic impact on geochemical conditions in the soils of the EAD related to waterlogging and alkalinization is shown on the map of water migration classes of chemical elements. The map was compiled using the data collected during soil sampling in 2010 (Fig. 5). In total, the combination of redox and pH conditions produced seven water migration classes, which are shown on the map.

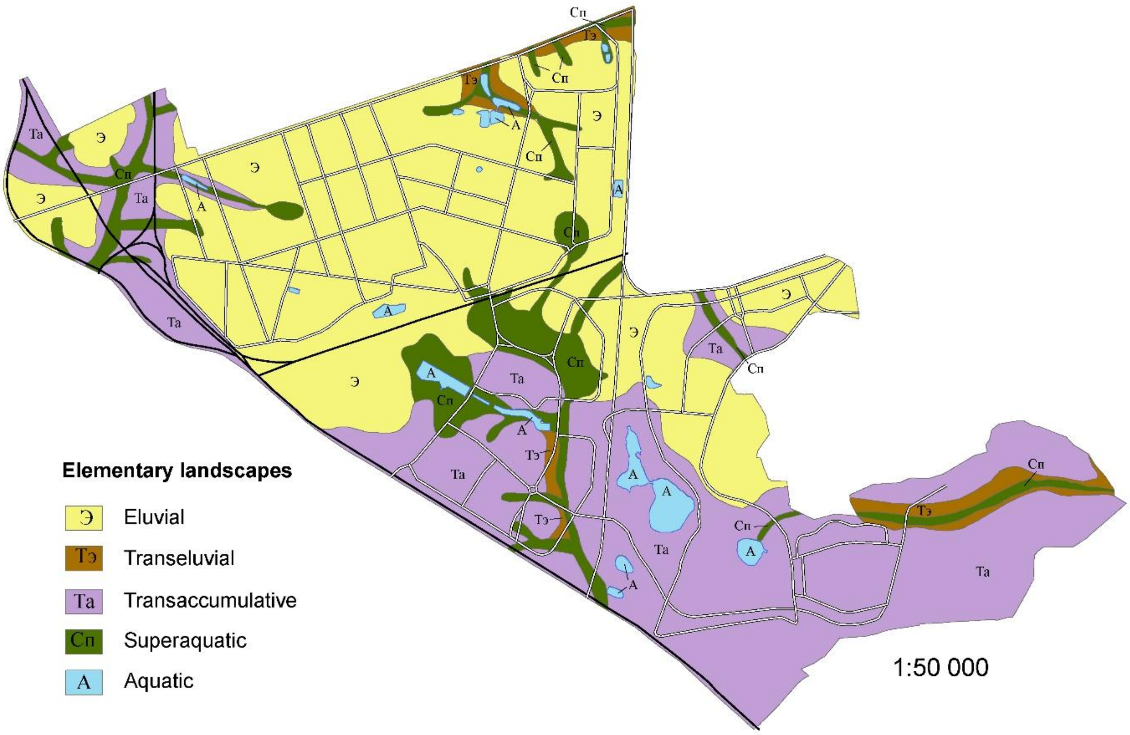


Fig. 4 The map of elementary landscapes of the EAD of Moscow

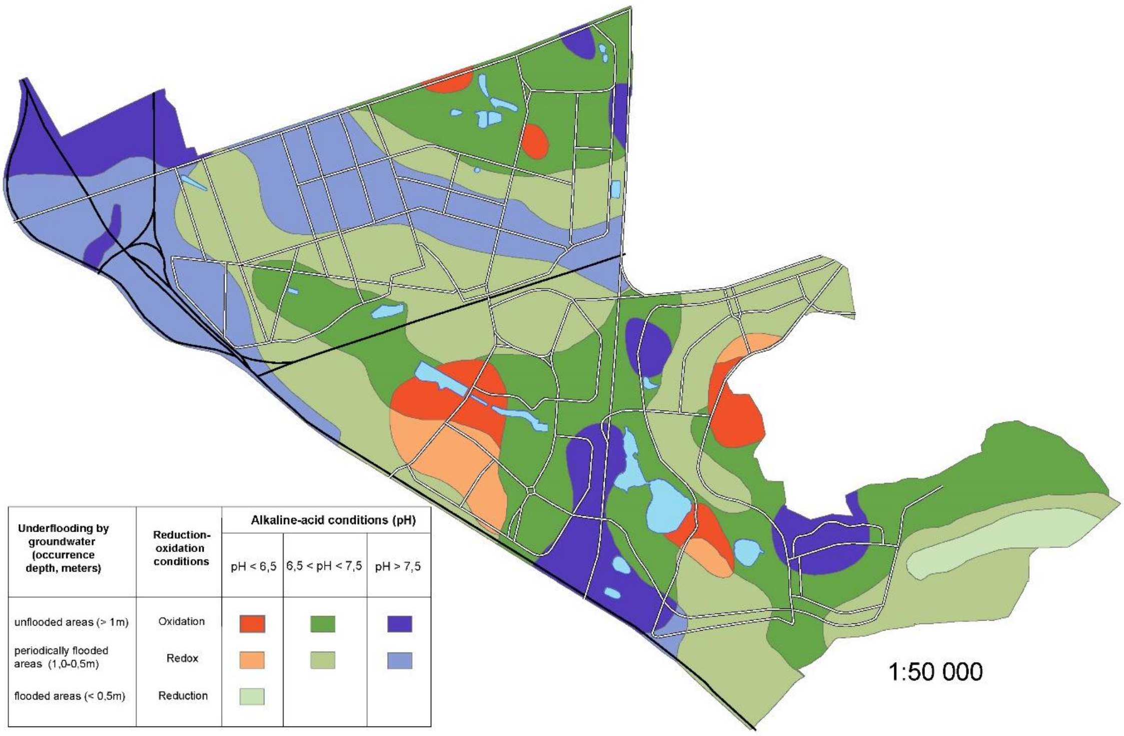


Fig. 5 The map of water migration classes of chemical elements in the soils of the EAD of Moscow

C. The Maps of Contamination of Soils and Snow Cover with Heavy Metals

Geochemical maps of this type display landscape-geochemical structure of the area under study. The levels of anthropogenic impact on the landscapes of the EAD of Moscow are characterized by the map of the integral index of the particulate precipitation of HMs on snow cover (Zd) and the map of the integral index of the soil pollution (Zc). For compilation of these maps the results of chemical analysis of snow and soil samples collected in 2010 according to a standard procedure [46] were used. Geochemical sampling of snow and soil cover with a spacing of 500-800 m made it possible to quantitatively assess recent levels of urban landscape contamination, identify spatial trends in HM distribution, and confirm the contours of anthropogenic anomalies.

Soil samples and snow filtrates were analyzed for concentrations of twenty HMs by mass spectrometry with induced coupled plasma (ICP-MS) and atomic emission spectrometry at the All-Russian Institute of Mineral Raw Materials (VIMS) using a Perkin-Elmer (USA) instruments.

The dust load on landscapes (Pn) was defined by the concentration of suspended matter in the snow. The integral index of atmospheric particulate precipitation of HMs was calculated using the formula $Zd=\sum Kd-(n-1)$, where $Kd=DX/Df$; DX and Df are the amount of particulate precipitation of elements (mg/km^2 per day) in the urban and background environments, respectively; and n is the number of accumulating metals with $Kd > 1.5$ [46]. Particulate precipitation of certain elements onto the snow was calculated as $D = Pn \cdot C$, where C is the concentration of an element in particulate matter (ppm).

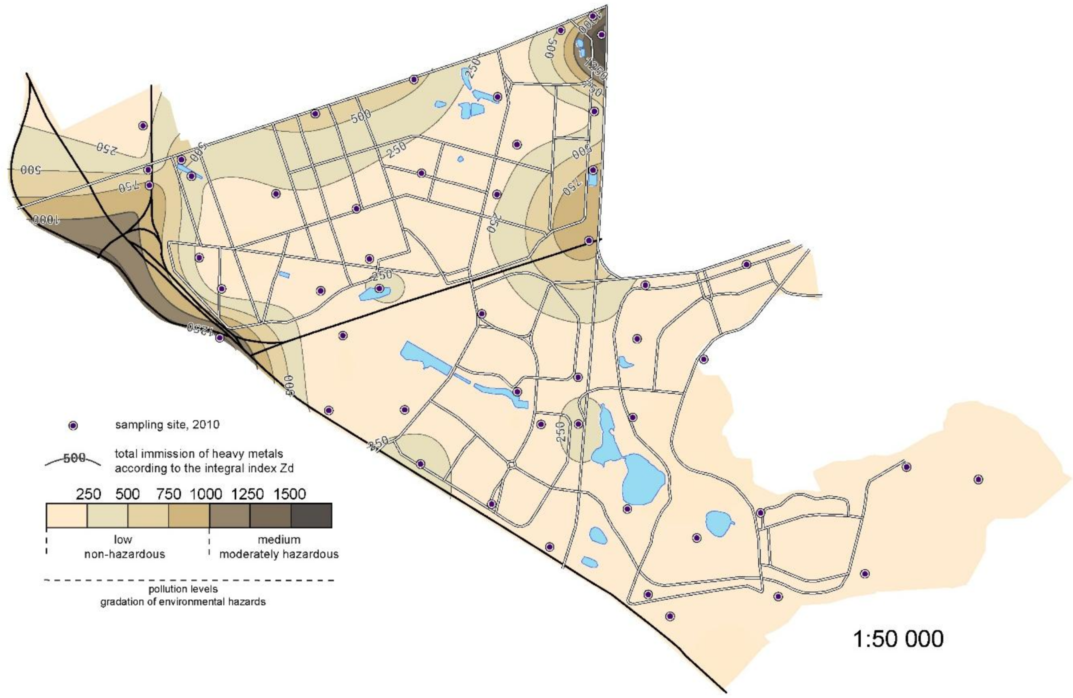


Fig. 6 Integral index of pollution of snow cover with HMs in the EAD of Moscow according to the particulate precipitation index Zd [41]

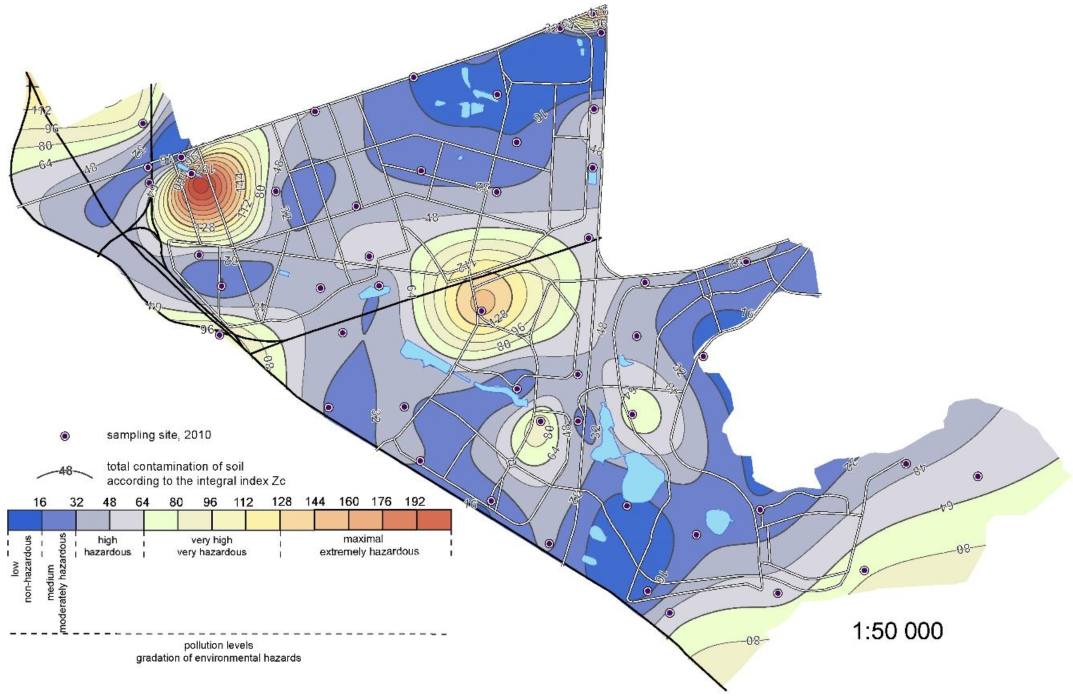


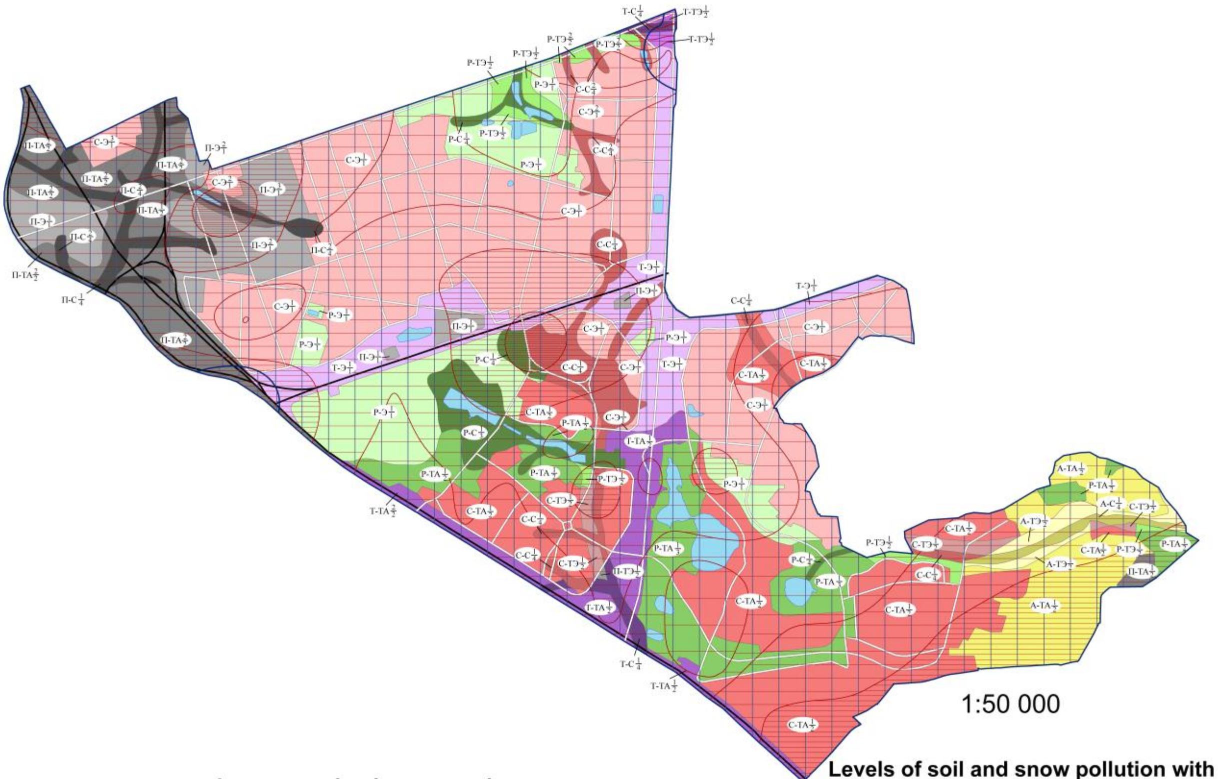
Fig. 7 Integral index of pollution of soils with HMs in the EAD of Moscow according to the particulate precipitation index Zc [41]

The levels of soil contamination with HMs were evaluated using the integral pollution index $Zc = \sum Kc - (n-1)$, where $Kc = CX/Cf$; CX and Cf are the average HM concentrations (ppm) in urban and background environments, respectively, and n is the number of accumulating metals with $Kc > 1$ [1].

The results for each of the 52 observation sites were included in the CDB for spline interpolation (Geostatistical Analyst, ArcGIS 9.3), which enabled spatial patterns of the integral index of HM pollution of snow cover and soils in the EAD area to be evaluated. As a result, digital models of anthropogenic anomalies [40, 41] based on Zd and Zc indices were created. Their cartographic representation is given in Figs. 6 and 7. The analysis of these models resulted in identification of anthropogenic sources of HMs and HM associations on the basis of accumulation intensity or metal behavior in the studied landscapes.

IV. THE USE OF A CDB FOR COMPILATION OF LANDSCAPE-GEOCHEMICAL MAPS OF URBAN AREAS

The database contains the blocks of interrelated digital maps is designed to support of integrated landscape-geochemical studies of urban areas. Such investigations entail the compilation of landscape-geochemical maps in which urban landscapes are classified in terms of migration and accumulation of pollutants. They also help to reveal environmental risk of landscape pollution in the various land-use zones of the city.



Lanscape - land-use complexes

Landscapes				Land-use zones				
Type	Class*	Elementary landscapes	Deposits**	Industrial (П)	Transport (T)	Residential (C)	Recreational (P)	Agricultural (A)
Urban outwash-moraine landscape of Meshchyora Lowlands	I	Eluvial (Э)	1/1	П-Э	Т-Э	С-Э	Р-Э	
	II	Transeluvial (ТЭ)	1/2	П-ТЭ	Т-ТЭ	С-ТЭ	Р-ТЭ	А-ТЭ
	III	Transaccumulative (TA)	1/2,3	П-ТА	Т-ТА	С-ТА	Р-ТА	А-ТА
	IV	Superaquatic (C)	1/3,4	П-С	Т-С	С-С	Р-С	А-С

Levels of soil and snow pollution with HMs. Ranks of environmental risk

Pollution levels / Rank of environmental hazards	Integral index of soil pollution (Zc)	Integral index of metal addition to snow cover (Zd)
low / non-hazardous	Zc < 16	Zd < 1000
medium / moderately hazardous	16 < Zc < 32	1000 < Zd < 2000
high / hazardous	32 < Zc < 64	2000 < Zd < 4000
very high / very hazardous	64 < Zc < 128	4000 < Zd < 8000
maximal / extremely hazardous	Zc > 128	Zd > 8000

*** Classes of water migration:**

I - Oxidizing-alkaline; II - Oxidizing-alkaline and neutral; III - Oxidizing-reducing - neutral and slightly acidic; IV - Reducing (gleic) - slightly acidic and acidic (neutralizable)

**** Deposits**

Numerator: Thickness of technogenic deposits, comprised mainly of loamy material with anthropogenic inclusions: 1 - < 1m; 2 - 1-3m; 3 - 3-6m

Denominator: Natural deposits: 1 - Fluvioglacial stony sands with shallow mantle loam on moraine; 2 - Paleoalluvial fluvioglacial sands and clayey sands with layers of loam ; 3 - Glacio- acustrine loams with layers of sand; 4 - Loamy-arenaceous deposits of gullies and cloughs.

Fig. 8 Landscape-geochemical map of the EAD of Moscow [48]

Geochemical classification of an urban landscape is used in the legend [2] and two major factors are taken into account: 1 – the intensity and the nature of anthropogenic loads from the major pollution sources, and 2 – landscape-geochemical conditions that control accumulation and dispersion of the polluting substances and, therefore, determining the impact effects.

The legend is constructed as a matrix. The land-use zones which characterize the intensity of HM input into landscapes are given in the right-hand part of the legend, and landscape and natural features governing water migration together with catenary patterns in HM distributions and the ability of heavy metals to accumulate at geochemical barriers are given in the left-hand part. The combination of these two parts enables the landscape-land-use zones to be distinguished. Their features determine the formation and magnitude of HM geochemical anomalies in soils and snow (Fig. 8). The shapes and boundaries of the anomalies are not the same in the two media since chemical features of snow cover reflects the present state of pollution, whereas soil cover in an urban environment accumulates pollutants over a period of many years.

Landscape-land-use complexes are displayed on the map in different background colors. The land-use zones are represented by individual colors, whereas the colors intensity gives the position of the elementary landscape within the catena: the more intensive the colors is, the lower the elevation of the landscape. Each taxon on the map is designated by an index which includes the name of the land-use zone, the kind of the elementary landscape, the composition and genesis of the deposits and the thickness of the anthropogenic layers. For example, the index ∏-Э1/1 indicates an eluvial landscape in an industrial zone formed on fluvioglacial stony sands, overlain by a cultural layer less than 1 m in thickness.

The intensity of snow and soil cover pollution with HMs is displayed on the map by contour lines using the integral indices of HM particulate precipitation (Zd) and soil pollution (Zc), represented in the geochemical map block in the CDB. Vertical blue hatching is used to show pollution of snow. Red hatching with different spacing depending on the level of pollution is used for soils. The size and the colors of the hatched areas indicate overlapping of anthropogenic anomalies in snow cover and soils.

V. CONCLUSIONS

Methods for specialized large-scale landscape-geochemical map compilation have been developed on the basis of land-use zoning and analysis of landscape and geochemical structure of the EAD in Moscow. Such maps display natural and anthropogenic factors and pollution levels in deposits. They show locations and sizes of anthropogenic geochemical anomalies in urban landscapes in relationship to emission sources, landscape-geochemical conditions, and the structure of lateral fluxes of polluting substances.

Landscape-geochemical maps of urban areas are compiled by assessment and generalization of a large amount of various cartographic materials which are arranged into interrelated blocks of digital maps in a cartographic database. The database includes a map of land-use zoning, which is compiled on the basis of high resolution satellite images and which contains a number of important characteristics necessary for environmental and geochemical investigations. Integrated GIS analysis of various maps of landscape structure revealed environmental features responsible for deposition of HMs and other pollutants in urban landscapes. Multielement geochemical maps display the spatial structure of anthropogenic anomalies of HMs in soils and snow cover of the studied area.

The proposed methods were tested in an urban ecosystem in the EAD of Moscow. The landscape-geochemical map and its contents were designed using GIS analysis and generalization of various nature and nature-anthropogenic maps. Its attribute table and legend contain anthropogenic factors of HM accumulation and dispersion, levels of pollution and grades of ecological risk with respect to the magnitude of urban landscape pollution.

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