GIS landscape-geochemical mapping of urban areas (with the example of Eastern Administrative Okrug of the city of Moscow)

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Abstract. The methodological approaches to compilation of landscape-geochemical maps for urban areas have been developed around cartographic database which systematizes digital maps presenting functional zoning of the study area, its landscape structure and technogenic anomalies of heavy metals. The methods have been tested during GIS landscape-geochemical mapping of Eastern Administrative Okrug of the city of Moscow. A landscape-geochemical map displaying the differentiation of urban landscapes in terms of conditions for heavy metal accumulation and according to contamination levels of soil and snow cover has been designed.

Keywords: GIS mapping, geochemistry of landscapes, urban areas

1. Introduction

Landscape-geochemical mapping is one of the most important components of ecological mapping of urban areas. Its theoretical and methodological basis is formed by geochemistry of landscapes and environmental geochemistry (Saet et al. 1990, Perel'man & Kasimov 1999). Rapid development of GIS methods and technologies opens up new possibilities for compilation of landscape-geochemical maps and allows to benefit from systematic approach in the analysis of various information on urban landscape structure and landscape functioning (Zhukov et al. 1999, Makarov et al. 2002, Kurbatova et al. 2004).

In the course of research large amounts of data on components of urban landscapes are accumulated. These data require structuring and systematical organization in order to improve efficient usability of the information. In addition there is a demand in providing information in the form of cartographic coverage, because maps provide the most complete spatial characterization of the study objects. Such cartographic support can be presented by the 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) GIS mapping of megalopolis landscapes by systematization of the data on landscape and functional structure in CDB.

2) on the basis of the designed CDB, developing and testing the methods of compilation of synthetic landscape-geochemical map displaying the differentiation of urban landscapes according to the conditions of higher-priority pollutant behavior and defining environmental hazard of landscape pollution in various functional zones of the city.

As the object of the study a territory of Eastern Administrative Okrug (EAO) of the city of Moscow with a number of large industrial zones and highways, local heat station, combustion plant and some other pollution sources has been chosen. Among the major pollutants of urban landscapes heavy metals (HMs) come to the forefront because many of them are considered to be highly toxic.

The research on HMs in soils, snow and vegetation on the territory of EAO has been conducted since 1989, enabling to evaluate long-term dynamics and spatial structure of pollution in landscape components (Kasimov et al. 2012, Labutina & Khaybrakhmanov 2012, Nikiforova et al. 2009-2011, Khaybrakhmanov 2011, Kasimov 1995). The results of the research provided the basis for the present study.

2. The structure of CDB for landscape-geochemical studies

Digital maps form the content of CDB, therefore it's important to determine the structure of attribute tables based on the types of both spatial (vector, vector-topological, raster) and graphic characteristics of objects (Luriye 2008). As a preliminary stage it is necessary to develop the structure and content of the map support system defining the logical structure of CDB.

The map support system was created for the territory of Moscow EAO. Multispectral QuickBird satellite images (2009) with spatial resolution of 2.4 meters, Ecological Atlas of Moscow (2000), cartographic and statistical Internet sources, data derived from geochemical soil and snow sampling served as the main sources of mapping.

The created cartographic material consists of the following blocks:

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

2) Maps of functional zones;

3) Maps of the landscape structure;

4) Geochemical maps.

Digital presentation of maps correspond to the established principles of GIS mapping including preliminary procedures for evaluating the quality of composed products, choosing symbolic systems, generalization, etc.

The rules for establishing connections between individual attribute tables are determined by database management system (DBMS). In our case, we used the DBMS ArcGIS 9.3 that provides management possibilities to deal with cartographic information. It defines the relational data model, which allows storing multiparameter spatial information in the form of related tables. Relations are defined by the columns of spatial objects' ID numbers on the map, which should be uniform for all interrelated objects. This approach causes the importance of using the system of basic spatial cells for the storage of information. These cells were functional zones allocated within current research project when designing map support system. Cell numbers are the same for different groups of indicators, spatially organized by functional 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 the convenient logical model that allows joint consideration of the information to analyze and compile new maps, especially complex and synthetic ones.

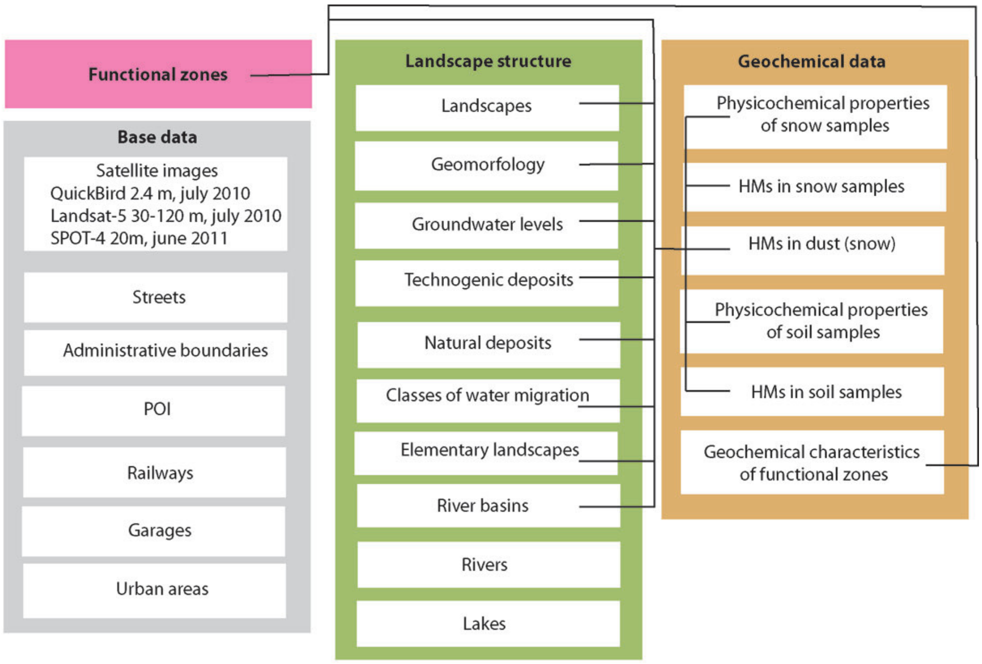


Figure 1. The logic structure of CDB

3. The content of the database blocks

3.1. Maps of functional zones

The type of urban land use plays a leading role in the formation of techno-genic geochemical anomalies of pollutants (Methodological guidelines... 2006), therefore in our research we developed the methods of functional zone mapping and compiled the map for EAO (Labutina & Khaybrakh-manov 2012, Khaybrakhmanov 2011). For the long time inventory data, various statistical data, topographical plans of cities have been the main sources of information. Updating the information, keeping it adequate was expensive and time-consuming. For the same reasons, aerial photography materials were not often used. Modern satellite images with spatial resolu-tion better than 5 m, being received with a several-day interval (GeoEye-1, WorldView-1, Ikonos, etc.) or even daily (RapidEye), have created the con-ditions for the development of remote sensing-based methods for the map-ping of urban areas (Aubrecht et al. 2009, Miller & Small 2003, Wilson et al. 2003).

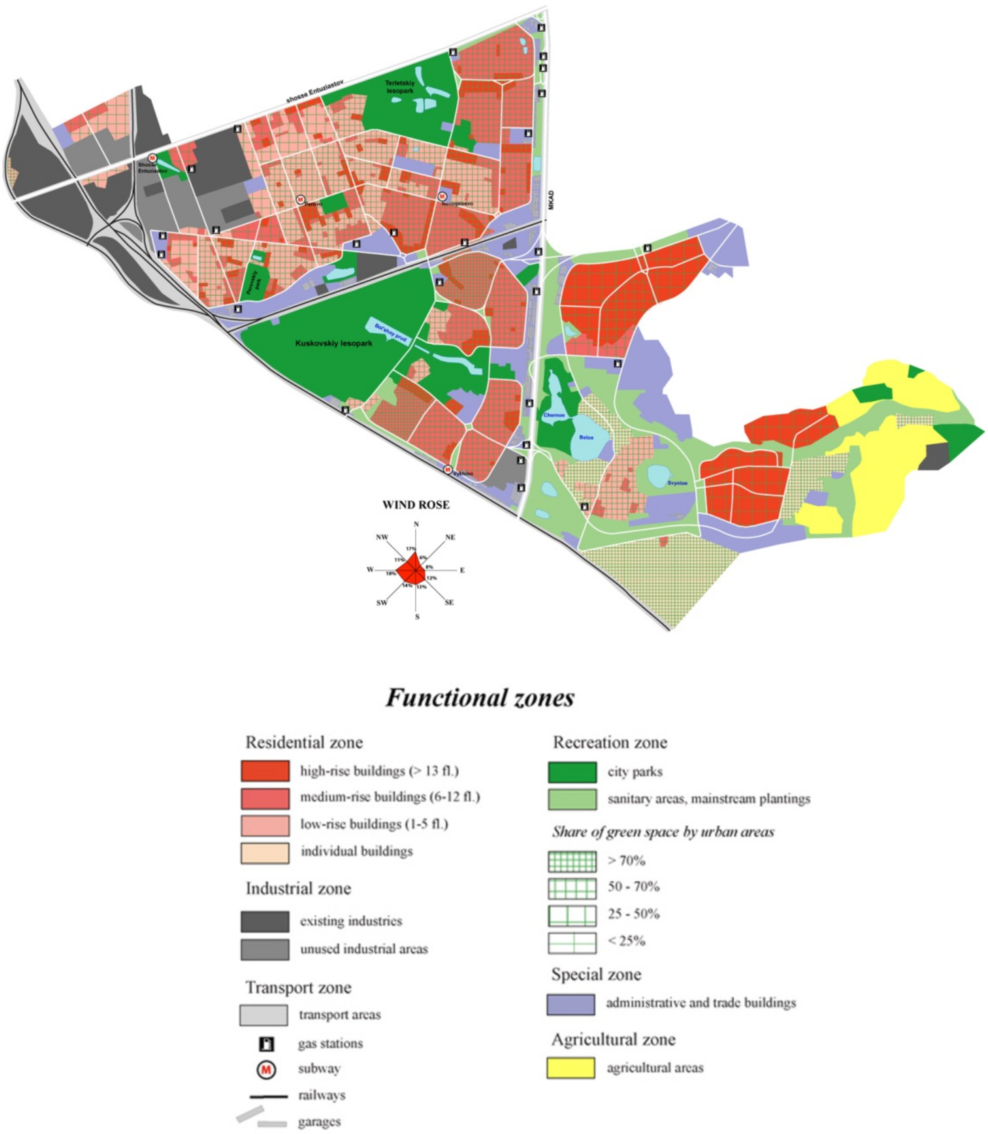


Figure 2. The map of functional zones for the territory of Moscow EAO

Many urban objects (individual buildings, streets, driveways, 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 also by logical deduction. At a lower resolution multispectral images indicate the properties of objects that are not visible on the black-and-white images.

The map of functional zones for the territory of Moscow EAO has the scale 1:50 000 (Fig. 2). The main data sources for this map are satellite images QuickBird (Digital Globe, USA) with a 0.61 m resolution in the panchromatic band and 2.44 m - in multispectral band. The methods of automated and visual interpretation were used in the process of mapping. Green areas and water bodies were identified on the basis of computer image classification (Guo 2007), the structure of residential areas and city functional zones - by visual interpretation.

The map of functional zones serves as a basis for revealing the factors of pollution and for the pollution assessment in the study area. During landscape-geochemical studies such map helps to perform task-oriented sampling, to identify the patterns of wind-induced dust transfer according to building locations and building clustering in residential areas. Besides it makes possible evaluating the impact of pollution sources on landscapes.

3.2. The maps of landscape structure

During landscape-geochemical mapping of urban areas not only functional zoning but also displaying natural conditions and their anthropogenic transformation are important since these factors eventually define the behavior and fate of toxicants and the dynamics of landscape pollution.

The major information on landscape structure of EAO was derived through the analysis and assessment of geological, geomorphologic, soil, vegetation, landscape maps from Ecological Atlas of Moscow (2000). In addition the maps designed by the authors were used (the maps of deposits, elementary geochemical landscapes, hydrous migration classes). All these maps were presented in a 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, GIS statistical analysis etc. As a result a set of maps characterizing landscape-geochemical relationships in urban landscapes was compiled.

The map of deposits. Quaternary deposits in the study area are overlain by technogenic and cultural layers. Since such layers impact chemical composition of soil cover and define initial levels of HM content they may contribute significantly to environmental and geochemical status of an urban landscape. For the analysis of deposit distribution over the territory of EAO the map displaying the differentiation of various (natural and technogenic) deposits in terms of their genesis, granulometry and thickness was designed.

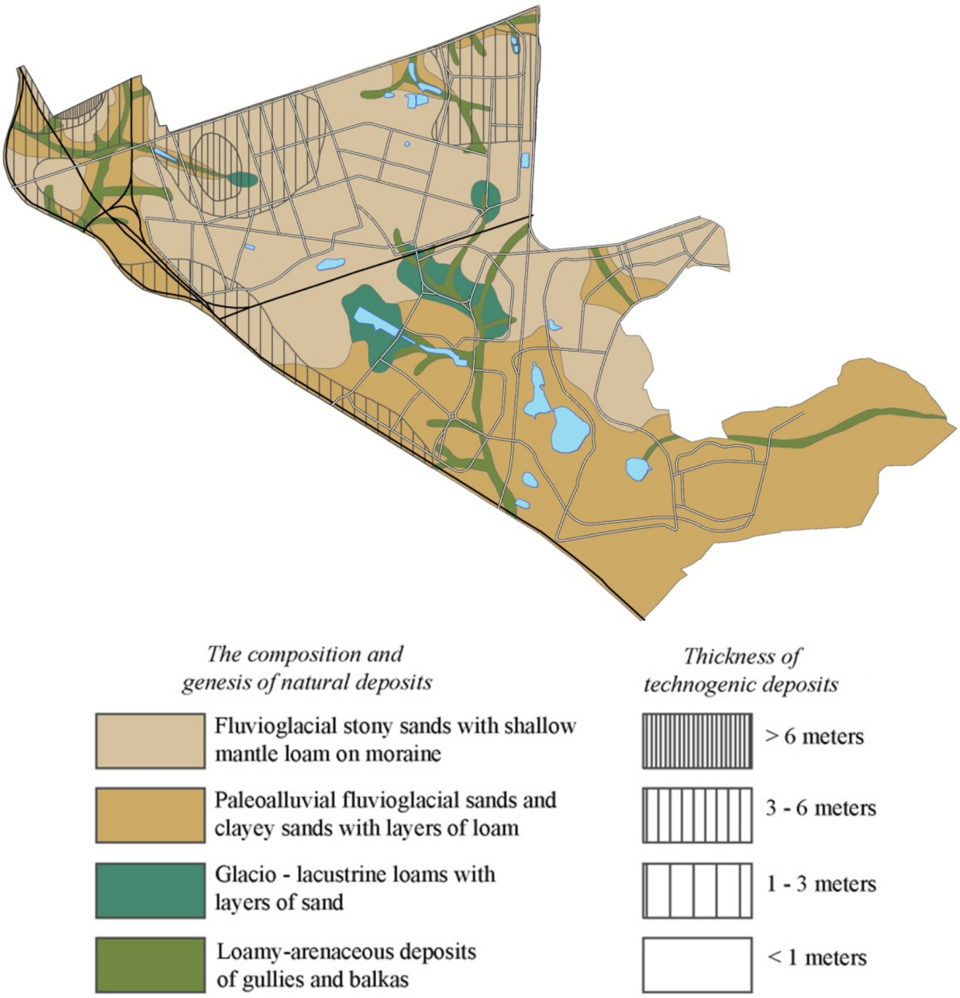


Figure 3. The map of deposits in EAO, the city of Moscow

The map of elementary geochemical landscapes reveals catenary geochemical structure of landscapes and characterizes direction of lateral fluxes of polluting substances in soil cover of the urban area between interfluve positions and related depressions (Fig.4). As a basis of the map content geochemical taxonomy of natural landscapes proposed by M.A.Glazovskaya was used (Glazovskaya 2002). Geochemical catenae between elementary landscapes reflect the variety of soil and slope processes and form certain paragenetic groups characterized by certain types of matter, energy and 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 5 gradations (genera) of elementary landscapes have been distinguished on the map of EAO: eluvial, transeluvial, transaccumulative, superaquatic and aquatic. Due to levelled relief, small altitude differences and high anthropogenic transformation of relief features transeluvial landscapes on the territory of EAO are rather rare and eluvial landscapes often border superaquatic ones (Fig. 4).

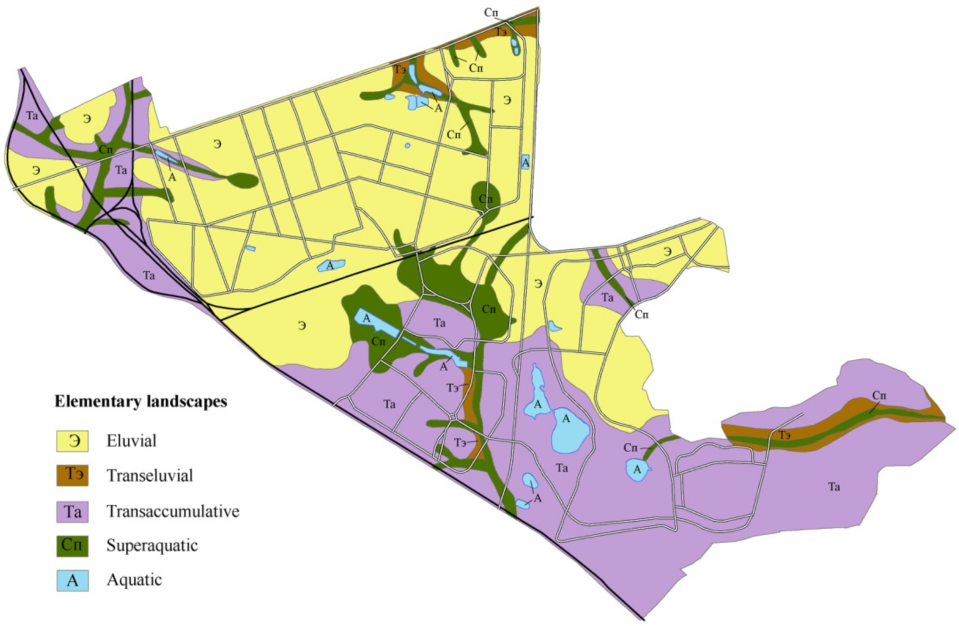


Figure 4. The map of elementary landscapes of EAO, the city of Moscow

The map of hydrous migration of chemical elements. The intensity of hydrous migration of pollutants in soils and subsoils is controlled by redox and acid-base conditions. The combination of various redox and pH settings produces 12 hydrous migration classes (Perel'man & Kasimov 1999). Anthropogenic impact on geochemical settings in soils of EAO, related to waterlogging processes and alkalinization, is shown on the map of hydrous migration of chemical elements. The map was compiled using the data collected during sampling in 2010 (Fig.5). In total the combination of redox and pH settings produced 7 hydrous migration classes which are shown on the map.

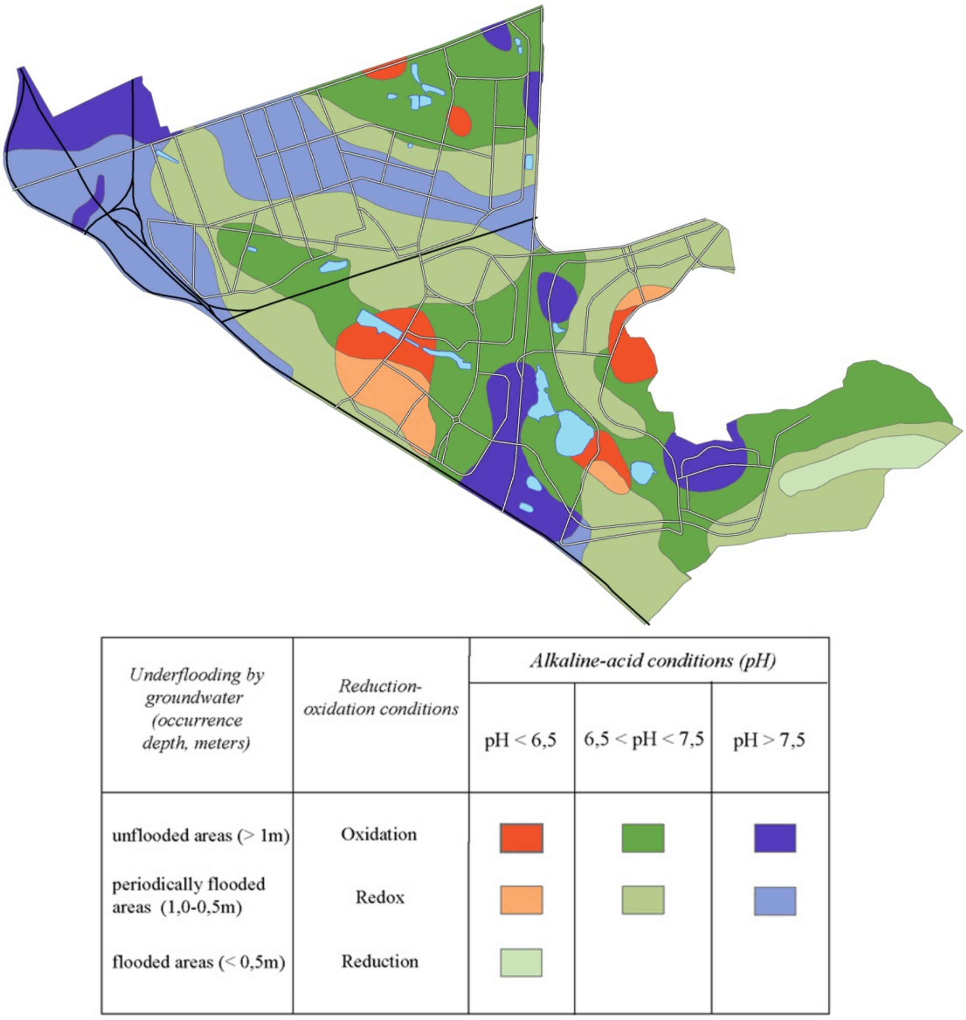


Figure 5. The map of the classes of hydrous migration of chemical elements in soils of EAO, the city of Moscow

3.3. 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 technogenic impact on the landscapes of EAO of the city of Moscow are characterized by the map of integral solid HM fallout onto snow cover (index Zd) and the map of integral soil pollution Zc. For compilation of these maps the results of chemical analysis of snow and soil samples, collected in 2010 according to standard procedure (Methodological guidelines... 2006), were used. Geochemical sampling of snow and soil cover with the applied spacing (500-800m) made possible a quantitative assessment of recent levels of urban landscape contamination, identification of spatial trends in HM distributions and confirmation of technogenic anomalies contours.

Soil samples and filtrates, containing solid phase of snow, were analyzed for concentrations of 20 HMs by mass spectrometry and inductively coupled mass spectrometry (ICP-MS) at All-Russian Institute of Mineral Raw Materials (VIMS) using Perkin-Elmer device, the USA.

Dust load on landscapes (Pn) was defined by concentrations of suspended matter in snow. The integral index of atmospheric addition (immission) of HMs was calculated using the formula $Zd=\sum Кd - (n-1)$, where $Кd=DX/Df$; DX, Df – fallouts of elements (mg/km2 per day) in urban and background environments respectively, n – the number of accumulating metals with Кd >1,5 (Methodological guidelines… 2006).

Fallouts of certain elements onto snow surface were calculated using the formula $D = Pn \cdot C$, where C is the concentration of an element in suspended matter (ppm). The levels of soil contamination with HMs were evaluated using integral index of pollution $Zc = \sum Кc - (n-1)$, where $Кc=CX/Cf$, CX, Cf – average concentrations of HMs (ppm) in urban and background soils respectively, n – the number of accumulating metals with Кc >1 (Saet et al. 1990).

The obtained results for each of 52 sampling sites were included into the CDB for spline interpolation (Geostatistical Analyst, ArcGIS 9.3) which enabled to evaluate spatial patterns of integral HM pollution of snow cover and soils on the territory of EAO. As a result digital models of technogenic anomalies (Kasimov et al. 2012, Nikiforova et al. 2011) based on Zd and Zc indices were created. Their cartographic representation is given on Fig.6 and 7. The analysis of these models resulted in identification of technogenic sources of HMs and isolation of HM associations on the basis of metal behavior or accumulation intensity in the studied landscapes.

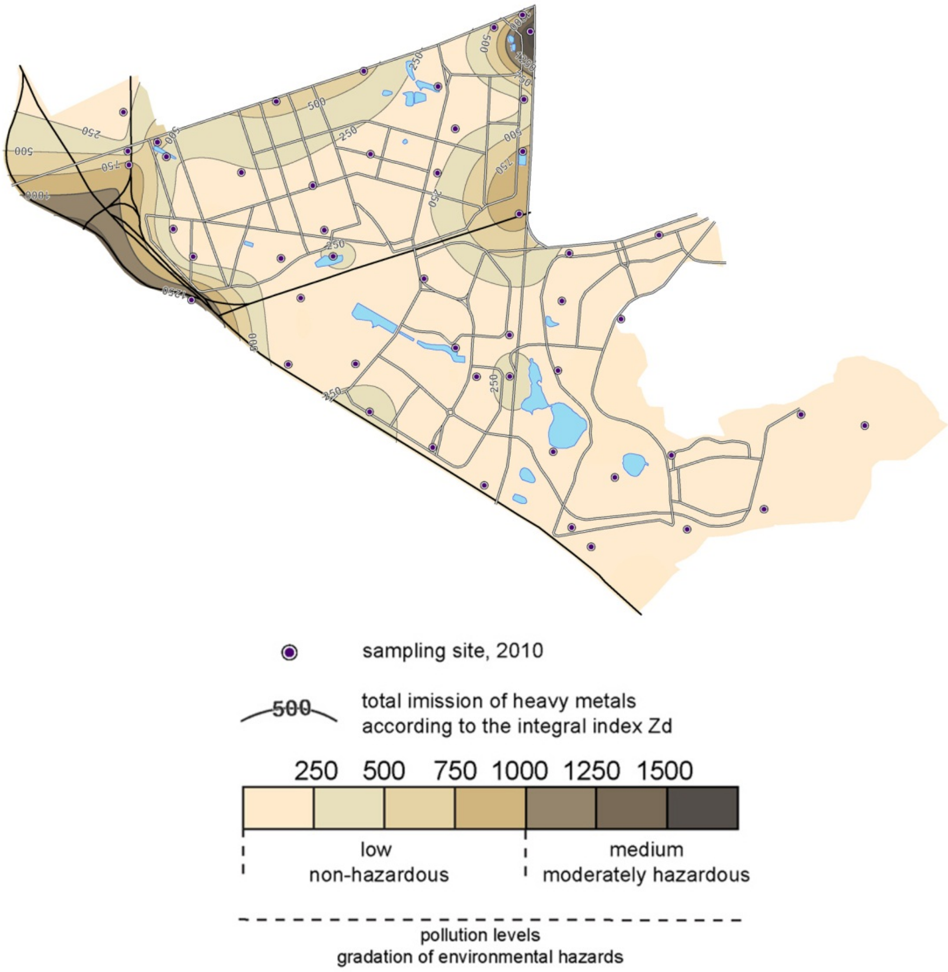


Figure 6. Integral pollution of snow cover with HMs in EAO of the city of Moscow according to addition (immission) index Zd

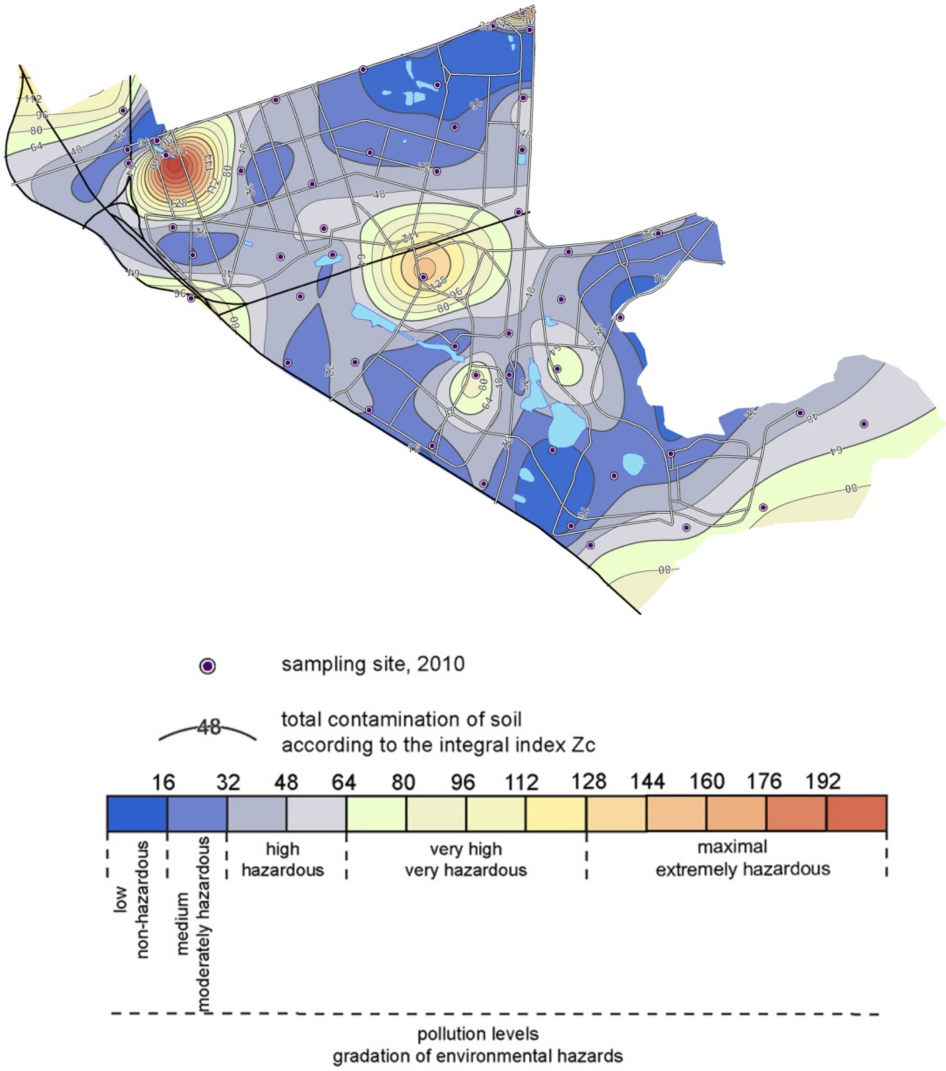


Figure7. Integral pollution of soils with HMs in EAO of the city of Moscow according to index Zc

4. The application of CDB for compilation of synthetic landscape-geochemical maps for urban areas

The database, comprising the blocks of interrelated digital maps, is designed to support integrated landscape-geochemical studies in urban lands. Such investigations suggest the compilation of synthetic landscape-geochemical maps which evaluate the differentiation of urban landscapes in terms of conditions of migration and accumulation of higher-priority pollutants. They also help to reveal environmental hazard of landscape pollution in various functional zones of the city.

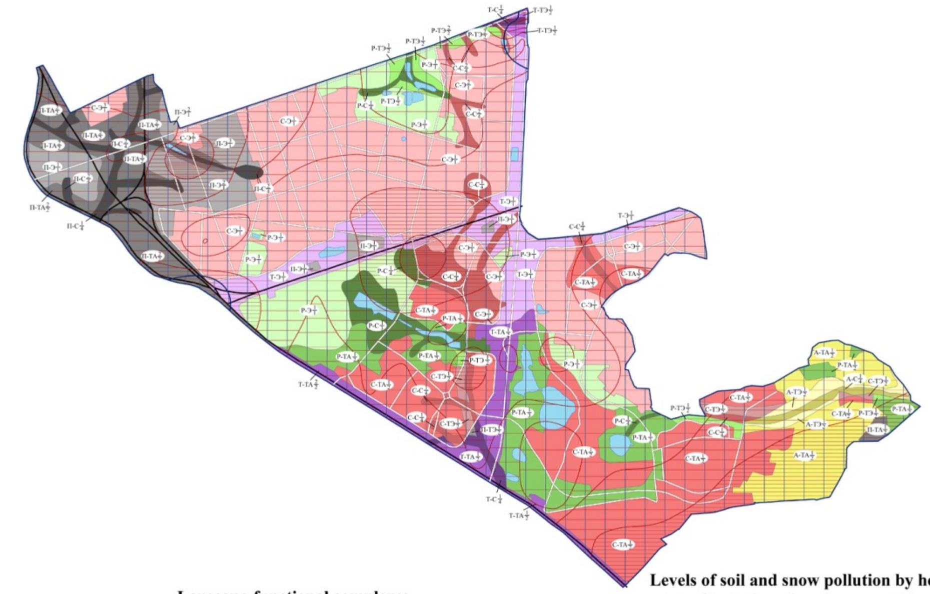
During compilation of large-scale landscape-geochemical maps for urban areas landscape-functional complexes as a major mapping units are used. The complexes are derived from nature and geochemical maps and from the map of functional zoning. Since functional zones are elementary spatial cells in the CDB, this can be done through combination of digital map contours using the overlay procedure and automatic generalization in GIS software.

Obviously in recent urban environment technogenic factors when compared to natural ones come to the forefront in terms of their impact on ecological situation (Zhukov et al. 1999, Perel'man & Kasimov 1999). It is confirmed by the values of rank correlation coefficients (r) estimated for the maps of soil and snow pollution compiled on the basis of Zc and Zd indices on one hand and the maps of functional zones and natural conditions on the other hand. Therefore during generalization of contours obtained through the overlay of the digital database maps, the contours were adjusted in accordance with those of functional zones.

Consequently the polygons of 20 landscape-functional complexes which attribute tables contain the information on landscape and functional structure of the territory were obtained (Fig.8)

In the legend geochemical classification of urban landscapes is used as a basis (Perel'man & Kasimov 1999) and two major factors are taken into account: 1– the intensity and the composition of technogenic loads defining the impact of major pollution sources, and 2 – landscape-geochemical settings, controlling accumulation and dispersion of the polluting substances and therefore determining the impact effects.

The legend is built in a matrix form. In the right-hand part of the legend the functional zones which define the addition of HMs into landscapes are displayed, and in the left-hand part landscape and natural features governing hydrous migration together with catenary patterns in HM distributions and the ability of HMs to accumulate at geochemical barriers are listed. The combination of these two parts enables to distinguish landscape-functional zones. Their features determine the formation and magnitude of HM geochemical anomalies in soils and snow (Fig.8). The shapes and the boundaries of the anomalies in different media are not uniform since chemical features of snow cover reflects the recent state of pollution whereas soil cover in urban environment accumulates pollutants during longer, many-years period.



Lanscape-functional complexes

Landscapes				Functional zones				
				Industrial-transport				
Type	Class*	Elementary landscapes	Species** (deposits)	Industrial (П)	Transport (Т)	Residential (С)	Recreational (Р)	Agricultural (А)
Urban outwash-moraine landscape of Meshchyora Lowlands	I	Eluvial (Э)	$\frac{1}{1}$	П-Э	Т-Э	С-Э	Р-Э	
	II	Transeluvial (ТЭ)	$\frac{1}{2}$	П-ТЭ	Т-ТЭ	С-ТЭ	Р-ТЭ	А-ТЭ
	III	Transaccumulative (ТА)	$\frac{1}{2,3}$	П-ТА	Т-ТА	С-ТА	Р-ТА	А-ТА
	IV	Superaquatic (С)	$\frac{1}{3,4}$	П-С	Т-С	С-С	Р-С	А-С

*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)

Levels of soil and snow pollution by heavy metals. Gradation of environmental hazards

Pollution levels / Gradation 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

**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 - lacustrine loams with layers of sand; 4 - Loamy-arenaceous deposits of gullies and balkas.

Figure 8. Landscape-geochemical map of EAO of the city of Moscow

On the designed map landscape-functional complexes are displayed by different background colours. A colour itself characterizes the assignment of the functional zone, whereas colour intensity identifies the position of the elementary landscape within the catena: the more intensive colour is the more subordinate position the landscape occupies. Each taxon on the map is designated by an index which includes the name of the functional zone, the genus of the elementary landscape, the composition and genesis of deposits and the thickness of technogenic layers. For example the index П-Э1/1 characterizes an eluvial landscape, located in an industrial zone, formed on fluvioglacial stony sands, overlain by cultural layer less than 1 m in thickness.

The intensity of pollution of snow and soil covers with HMs is displayed on the map by contour lines using integral indices of HMs immission Zd and soil pollution Zc, represented in geochemical block of maps in the CDB. To show pollution of snow vertical blue hatches are used. For soils red hatches with different spacing depending on the level of pollution are applied. The size and the colour of the hatched areas indicate cross location of technogenic anomalies in snow cover and soils.

5. Conclusion

On the basis of functional zoning and the analysis of landscape and geochemical structure of EAO in the city of Moscow the methods of specialized large-scale landscape-geochemical map compilation have been developed. Such maps display natural and anthropogenic factors and pollution levels in depositing media. They show locations and sizes of technogenic geochemical anomalies in urban landscape in relation to impact sources, landscape-geochemical settings and direction of lateral fluxes of polluting substances.

The compilation of landscape-geochemical maps for urban areas is performed by assessment and generalization of considerable and various cartographic materials which are arranged into interrelated blocks of digital maps in CDB. The database includes the map of functional 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 enabled to reveal environmental features responsible for indication and deposition of HMs and other pollutants in urban landscapes. Multi-elemental geochemical maps display spatial structure of technogenic anomalies of HMs in soils and snow cover of the studied area.

The proposed methods have been tested with the example of urbanized ecosystem located in south taiga – EAO of the city of Moscow. Using GIS analysis and generalization of various nature and nature-anthropogenic maps the landscape-geochemical map and its content have been designed. Its attribute table and the legend comprise natural and technogenic factors of HM accumulation-dispersion, levels of pollution and grades of ecological hazard in terms of urban landscape pollution magnitude.

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