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NEW APPROACHES TO THE DEVELOPMENT OF METHODOLOGY FOR ANALYSIS OF STRUCTURAL-GEOMORPHOLOGICAL COMPLEXES FOR THE PURPOSES OF URBAN PLANNING (BY THE EXAMPLE OF THE TERRITORY OF MOSCOW)

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Abstract: Methodology for an analysis of structural-geomorphological complexes based on the engineering geological zoning and taxon system makes it possible to distinguish megamassifs with uplift and subsidence tendencies, to estimate and analyze the manifestations of exogenous processes in the city territory using the set of geomorphometric indicators by taxa.

Keywords: Engineering geological zoning; structural-geomorphological complexes; taxonomic formula of hazard; main geomorphological indicators; geoecological image of city.

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INTRODUCTION

The urban development is largely based on the efficient use of the peculiarities of a natural territorial complex including the understanding of the geoecological peculiarities that include the geomorphological peculiarities, endogenous and exogenous factors of geological environment, the complexity of engineering geological conditions, and the distribution of the distribution of hazardous geological processes. This thesis is being developed in line with a notion of "urban geology" (Legget, 1973, 1987) that emerged in the 60-es of the XX century; gradually, with growing awareness of the role and importance of the geological sciences for urban development planning, it grew into a mature scientific discipline. Starting from the 10th congress, the International Association for Engineering Geology and the Environment (IAEG), the leading scientific organization on this problem, holds sessions as part of the scientific programs of its congresses, devoted to the problems and development of the urban geology primarily based on the methods of engineering geological zoning and the reduction of geological risks for urbanized territories (Mulder, 2001, Pereyra, 2003, Rauh, 2008).

It should be noted that the issues of the urban geological structure, the generation, and use of the required geological data were first formalized in the International Project "Integrating Geological Information in City Management to Prevent Environmental Risks" (GeoInforM) as part of the EU program Life – Third Countries (Bogdanova, 2009, Shtokalenko 2009, Spiridonov, 2009). In contrast to other world's megacities, Moscow city authorities adhere to the procedure of keeping the unified city Geofund where the engineering geological survey data obtained in the city territory has been stored for over 150 years[1]. Namely, this circumstance made it possible to implement a unique large-scale geological mapping project for the territory of Moscow (Osipov, 2011, Mironov 2011, Innovative project, 2012) and, with the project advancement, to further promote the geoecological studies (Karfidova, 2016, Mironov, 2017, Bachurina, 2017), develop the required limits (Zaikanov, 2018) and estimate the geological risks (Kozliakova, 2019, Geological risk, 2020).

A hierarchical system was developed as part of the engineering geological zoning map on a scale of 1 : 10 000 based on the methods of selecting taxa by the structural-geodynamic features and delineating the structural-geomorphological complexes (Grigoryeva, 2010, Makarov, 2011). The considered structural-geomorphological complexes represent a basis for the geological environment and the city landscape structure; the corresponding natural territorial complexes are conditioned by the city landscape genesis. Such an approach corresponds to the rules formed and developed by the scientific direction of M.V. Lomonosov Moscow State University to solve the problems related to rational use and protection of the geological environment: "...as a rule, the engineering geological territory zoning is conducted on the principals of regional or ***typological genetic-morphological zoning***. It makes it possible to single out the homogeneous territories according to all the factors of engineering geological conditions, accordingly anthropogenic changes within each of them shall have their particular features and dependencies"(Golodkovskaya, 1978; Sergeev and Golodkovskaya, 1978, Sergeev, 1988). The adopted procedure for **updating engineering geological zoning maps** is of fundamental importance in the use of engineering geological zoning during urban planning.

This proposed approach is employed to develop "**geoecological image**" of the city which is necessary to tackle the spatial planning issues and ensure that the city develops in a sustainable way[2] (Karfidova, 2019).

Initial data

The initial data includes a database on the wells drilled during geological engineering surveys, mapping materials as part of the Moscow geological mapping project; an integrated engineering geological zoning map on a scale of 1 : 10 000; a digital terrain model (DTM) of Moscow territory calculated according to the open data from the Shuttle radar topographic mission – SRTM 90 m (Shuttle radar topographic mission)[3], a DTM cell size – 100 m; a surface runoff model derived from the DTM (Osipov, 2016) including surface runoff accumulation zones and locally closed topographic lows (Karfidova, 2019).

A hierarchical system of the engineering geological zoning map which is used for identifying the structural-geomorphological complexes is shown in **Table 1**. The innovative approach used for developing this hierarchical system is to identify megamassifs according to a geodynamic principle with opposing tendencies: megamassif A – a territory with a tendency to raise and megamassif B – a territory with a tendency to down.

Macromassifs are subdivided into the depositional plains of a **glacial** complex: taxon I – moraine, fluvioglacial and moraine-fluvioglacial and taxon II – lacustrine, lacustrine-boggy and erosion-accumulative plains.

For the **alluvial** complex taxa III, IV, V have been identified – respectively, the third, second, and first

[1] Instructions (2004) for engineering-geological and geoecological surveys in Moscow. Government of Moscow (in Russian).

[2] International guidelines (2019) on urban and territorial planning. https://unhabitat.org/sites/default/files/download-manager-files/IG-UTP_English.pdf Accessed 28 January2022

[3] https://srtm.csi.cgiar.org/srtmdata/

Table 1. The hierarchical taxa system of the structural-geomorphological complexes according to engineering geological zoning

Geological engineering zoning map											
Megamassif A – territory with a tendency to raise including the southern slope of the Klinsko-Dmitrovskaya ridge and the Teplostan Upland						**Megamassif B** – territory with a tendency to down including the structural trough of the Moscow-Meshchera moraine-fluvioglacial plain and alluvial terraced plains.					
Macromassif						Macromassif					
Glacial complex			Alluvial complex			Glacial complex			Alluvial complex		
A-I	A-II	A-III	A-IV	A-V	A-VI	B-I	B-II	B-III	B-IV	B-V	B-VI

terraces rising above the floodplain and VI – a floodplain terrace of Moskva River and its tributaries.

The following factors are essential for analyzing taxa in the structural-geomorphological complexes within Moscow territory and comparing megamassifs A (uplift) and B (subsidence) and macromassifs of the glacial and alluvial complexes:

- The engineering geological complexity distribution through the city territory (Karfidova, 2020),
- The distribution of structural-geomorphological complexes on the territory of Moscow by taxa.
- The distribution of taxa on Moscow territory is shown in **Fig. 1**.

An update of the engineering geological zoning map is based on the use of data from engineering geological surveys of new construction, which are driven by the dynamics of a rapidly changing city like Moscow. The procedure for updating a map stem from the spatial planning tasks, however, at present, it is unfortunately not defined by any administrative document of the Moscow City Government. Initial data is put to use in the process for establishing a procedure for employing the proposed city planning methods; at that it is worth noting how important is the user access regime with regard to the engineering geological zoning data and the development of appropriate measures of electronic interaction between the information source operator and the city users **(Fig. 2)**. Essentially, the most actual task is to develop a common culture of the city environmental management including the city services the regulations of which should advisably determine a query to the city information resource.

Glacial complex: 1 – I taxon, 2 – II taxon,
Alluvial complex: 3 – III taxon, 4 – IV taxon, 5 – V taxon, 6 – VI taxon.

In the diagrams: megamassif A – blue, megamassif B – brown.

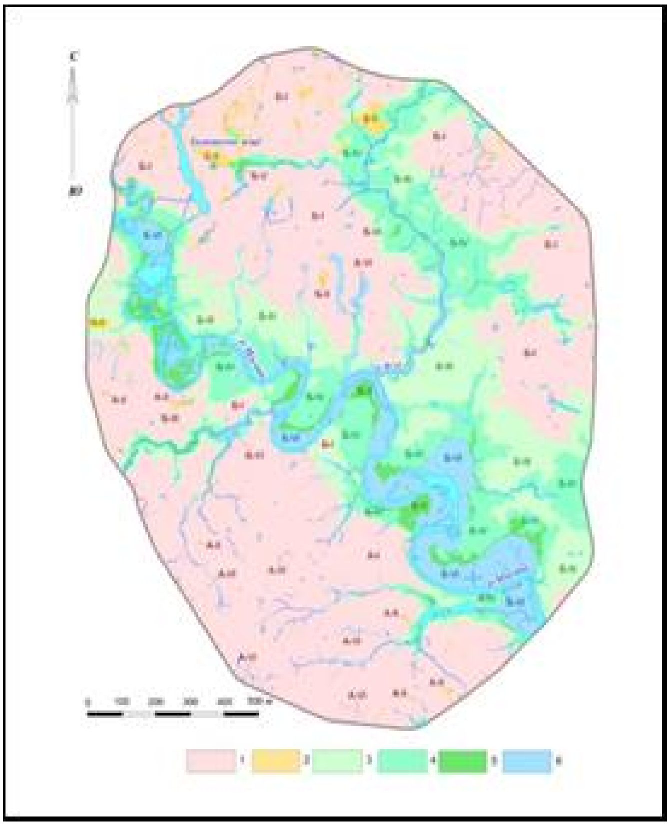

Fig.1. Schematic map of the distribution of structural-geomorphological complexes on the territory of Moscow by taxa (within the Moscow Ring Road).

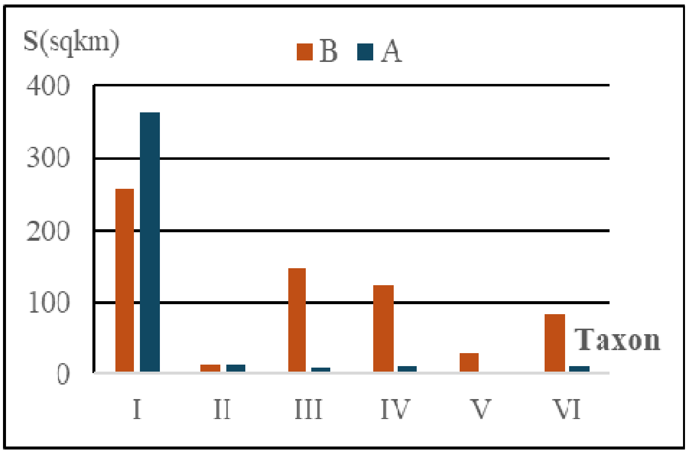

Fig.2 Diagram of distribution of mega massif's area by taxa.

Calculation and analysis methods

This research approach is based on the assumption of importance of the structural-geomorphological complexes in terms of features of the geological environment and natural territorial complexes of the city landscape in relationship with the city's economy (first of all, the city environmental management economy) and its sustainable development. Computational research procedures based on the use of traditional spatial analysis methods are realized on the GIS platform and are aimed at developing the unified city digital platform.

Polygons of the macromassif taxa of the engineering geological zoning map are used for analysis the structural-geomorphological complexes. The spatial-analytical indicators are sufficiently well defined in the geomorphological mapping methods and are normally included in the mandatory functions portfolio of GIS systems (Moore, 1991, Geomorphometry, 2009, Argyrioua, 2016). It is proposed to define a minimal set of mandatory indicators in the set of characteristic indicators for the structural-geomorphological complexes which will describe the city landscape in vertical and planar planes and distribution of the city landscape vulnerability to the exogenic processes (**Table 2**). The analysis of digital terrain model and generation of surface runoff model make it possible to calculate the locally closed subsidence zones (depressions) and the surface runoff accumulation zones (Karfidova, 2019). When analyzing the considered structural-geomorphological complexes, it is essential to consider spatial relations between the hazardous geological process zones and surface runoff accumulation zones. Climate changes and increased cases of extreme precipitation justify the relevance of such an analysis, especially bearing in mind the cases when the increased precipitation becomes a trigger factor for the geological hazardous process. Neighborhood analysis methods are used for calculating the vertical and planar roughness evaluation – surroundings of 3 neighboring cells, which corresponds to an area of 0.1 sq. m at original DTM. The small area is conditioned by small dimensions of taxa of the flood plain and above flood-plain terraces.

What is essential for the implemented approach is a geostatistical analysis of the distribution of indicators across the macromassif taxa which include statistical evaluation calculations for the distribution indicators (minimum, maximum, medium values, standard deviation, distribution frequency, and an assumption about the distribution law for the considered values).

It is proposed to consider the formulation of a taxonomic formula of geological process hazard on the territory of a macromassif (according to the formulation of a taxonomic formula for species composition of a forest area generally accepted in the forest practice) to be one the most important informational characteristics of structural-geomorphological complexes. The compilation of a taxonomic formula for the hazardous geological processes on the territory of a macromassifs (according to the practice of compiling a taxonomic formula for the species composition of a forest massif, accepted in forest practice) is proposed to be attributed to the most important informative characteristics of structural-geomorphological complexes. Such a formula shall make it possible to evaluate the importance and to sort the types of hazardous geological processes in descending order for a megamassif and then to evaluate the possibility of comparing the taxonomic formulae of megamassifs.

Formulating a taxonomic formula of geological hazard for the considered region territory is performed as follows:

$$K1OP1,\ K2OP2,\ K3OP3\ \ldots, \qquad (1)$$

where K1> K2 > K3 – percentage (integer part) of the area occupied by dangerous geological processes (OP1, OP2, OP3…) in descending order. Shown in square brackets are the codes of hazardous geological processes used in the engineering geological zoning map of Moscow: 1 – underflooding, 2 – shallow landslides, 3 – potential karst-suffosion, 4 – karst-suffosion, 5 – deep landslides, 6 – technogenic soils, and 7 – weak soils. The curly brackets are present at the end of the formula between which the codes of hazardous processes occupying less than 1% of the territory are shown.

Analysis of the distribution of indicators across the macromassifs within the megamassifs with tendencies to raise (A) and down (B) includes the following tasks:

1) Calculation of the indicator distribution depending on a taxon (from 1 to 6);
2) Calculation of the indicator tendency line;
3) Calculation of the surface runoff accumulation zones;
4) Calculation of a taxonomic formula of geological process hazard;
5) Analysis of indicator interrelation between megamassifs A and B;
6) Comparative analysis of totality of calculated indicators for megamassifs A and B,
7) Conclusions on the main properties of structural-geomorphological complexes.

Table 2. The set of mandatory indicators for structural-geomorphological complexes.

Type of indicator	No.	Indicator name	Unit of measurement
I. Geomorpho-metric indicators	1.	Evaluations of absolute elevation marks of ground surface, m	H (m)
	2.	Evaluations of vertical roughness or index of topographic roughness of relief – TRI	TRI (m/sq. km)
	3.	Evaluations of planar roughness PRI (m/sq. km) by a sum of water flow lengths of surface runoff per unit area – PRI*	PRI (m/sq. km)
	4.	Evaluations of hypsometric index – HI	HI (-).
II. Hazardous geological process indicators.	5.	Evaluation of a specific share of dangerous geological processes by taxon area – Phaz.	Phaz (%)
	6.	Evaluation of a specific share of particular dangerous geological processes in the area of surface runoff accumulation zones – Rac-hz*.	Rac-hz (%)
	7.	Taxonomic formula of geological hazard process	

* Indicator calculation is based on a surface runoff model.

The proposed methods are implemented in the geographic information system environment, the calculated evaluations of indicators and taxonomic formula are included in an additional taxa table of the engineering geological zoning map database.

Analysis results

The calculation results of the distribution of the geomorphometric indicators by taxa of the macro-massifs are shown in **Figs. 3-6**. A uniform representation of the macromassifs is used in Graphs 3-6: Macromassifs: A (blue) and B (brown).

Analysis of the plotted graphs for the geomorphometric indicators allows noticing the following:

- A general tendency to decrease the absolute elevations from the first taxon to the sixth taxon; rate of elevation decrease is higher in the glacial complex as compared with the alluvial complex; the elevation marks of megamassif A are higher as compared with the marks of megamassif B by 10-13 m (**Fig. 3**);
- The values of topographic roughness index TRI varies within a range of 10-20 m, values of TRI in megamassif A are higher as compared with megamassif B by 6-9 m (**Fig. 4**);
- The values of planar roughness PR vary within a range of 0.1-0.8 km/0.1 sq. km, the exception is the value of 1.8 km/0.1 sq. km for the floodplain of megamassif A which is explained by the steep slopes of small rivers within megamassif A (**Fig. 5**);
- A general tendency to decrease hypsometric index HI within a range of 0.6-0.3 from taxon 1 to taxon 6 (**Fig. 6**). This is also explained by the steep slopes of small rivers in megamassif A.

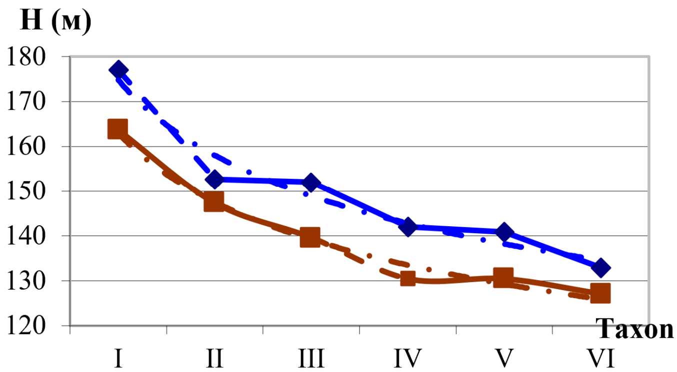

Fig. 3. Graph of the distribution of absolute elevations of the earth's surface relief by taxa. The dotted line shows the calculated trend lines.

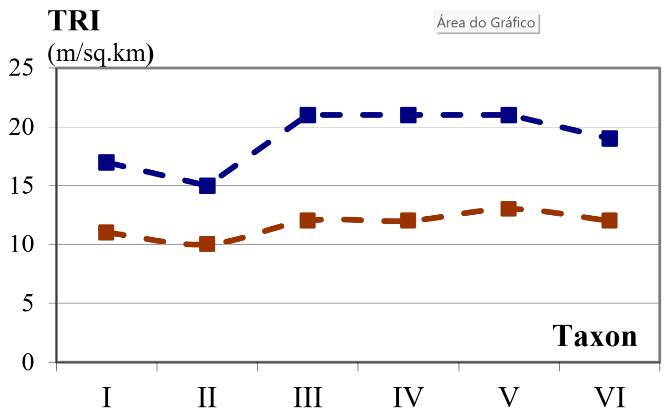

Fig. 4. Graph of the distribution of TRI by taxa.Correlation coefficient between Mega massifs A and B R^2= 0.91.

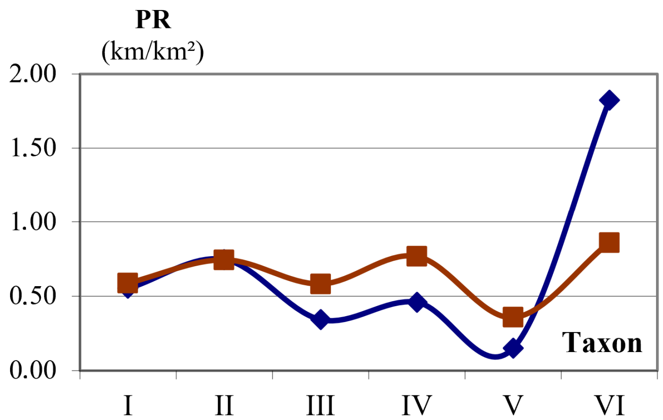

Fig. 5. Graph of the distribution of PR(km/ sq.km) by taxa.Correlation coefficient between Mega massifs A and B R^2= 0.76

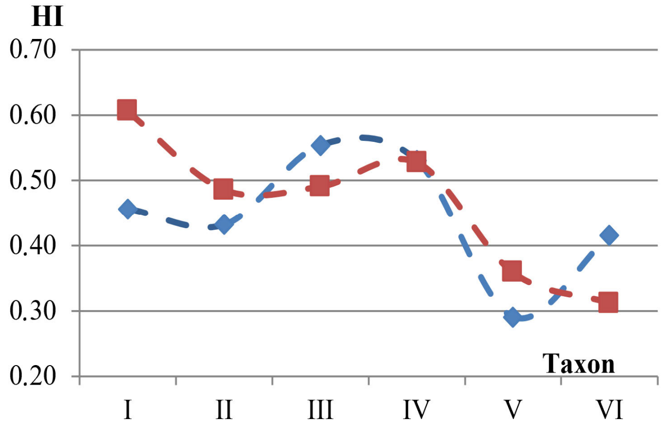

Fig. 6. Graph of the distribution of erosional ruggedness on hypsometric index HI. Correlation coefficient between Mega massifs A and B R^2= 0.74.

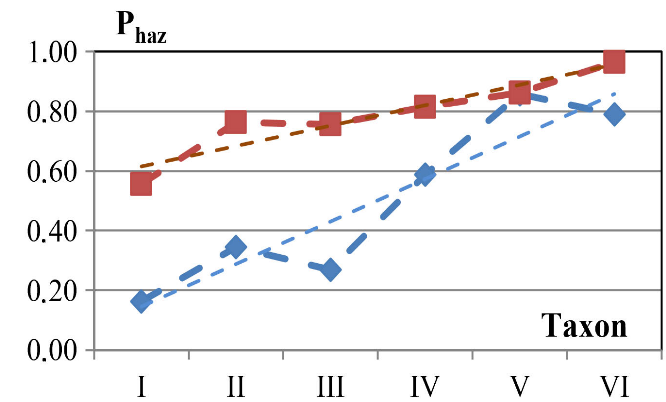

Fig.7. Graph the proportion of hazardous geological processes in area of taxon P_{haz} by taxa.

The calculated coefficients of determination between the considered indicators of structural-geomorphological complexes A and B – R > 0.7 which demonstrates a significant relationship between the complexes and corresponds to the methodological basis of the engineering geological zoning.

Analysis of the graphs of specific shares of the hazardous geological processes in a taxon area showed that the indicator values for megamassif B are considerably higher than the values in megamassif A; the general trend of the linear growth of P_{haz} indicator, at that the growth rate of the indicator for megamassif A (P^{A}_{haz}) is 2 times higher than the growth rate for megamassif B (P^{B}_{haz}) (**Fig. 7**); the coefficients of determination between the indicators R^2= 0.76. The calculated coefficients of determination between the considered indicators of complexes A and B – R > 0.7 reflecting a significant relationship between the complexes which corresponds to the adopted methodological basis of the engineering geological zoning.

Analytical results of the relationship of surface runoff accumulation zones with hazardous geological processes Rac-hz are shown in **Fig. 8.**

The graphs allow noticing a sharp distinction in the distribution of accumulation zones on the territory of megamassifs A and B:

- These processes were not observed over 74% of megamassif A territory while for megamassif B it was 32%.
- On the territory of megamassif B the accumulation zones related to the underflooding processes occupy 2.5 times bigger area than on territory of megamassif A.

The set of hazardous geological processes for megamassif A differs from that of geological processes within megamassif B which includes the processes of hydrogeological nature (in descending order): underflooding, potential karst-suffosion, and a complex process of combined manifestation of the underflooding and potential karst-suffosion.

The results of the comparison of taxonomic formulae are shown in **Table 3**.

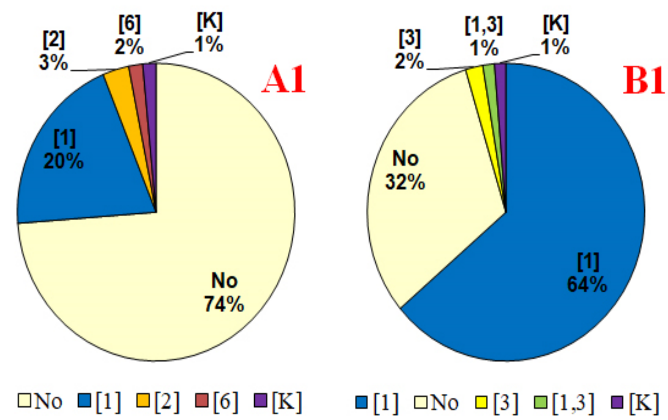

Fig. 8. The diagram of relationship between the accumulation zones of surface runoff with hazardous geological processes for macromassif A-I (left), for macromassif B-I (right).

Table 3. Taxonomic formulae of dangerous geological processes for megamassifs

Taxon	Taxonomic formula of megamassif A	Taxonomic formula of megamassif B
I	12[1]1{2;6}	50[1]44[3]3[1,3]1[4]
II	35[1]	57[1]12[1,3]4[3]1{1,7;7}
III	24[1]2[6]1[2]	40[1]19[3]8[1,3]3[4]1{1,7;7;3,6}
IV	50[1]5[1,5]1{5;6;1,2}	33[1]24[3]18[1,3]3[1,7]1{1,3,7;3,6}
V	85[1]1[1,6]	36[1]27[3]19[1,3]1{3,7;3,6;1,2}
VI	75[1]4[6]2[1,6]1[1,2]	38[1,3]37[1]14[3]2[1,3,6]2[3,6]1{1,6;1,7}

Difference of the taxonomic formulae between the megamassifs is most pronounced in the glacial complex: on the territory of taxon I of megamassif A the hazardous geological processes occupy 13%, in megamassif B – 98%, respectively, on the territory of taxon II the dangerous geological processes occupy 35% and 74%. In the alluvial complex on the whole the hazardous geological processes occupy larger territories as compared with the glacial complex, at that taxon VI territories (floodplains) are the most vulnerable territories to the hazardous geological processes. It is necessary to note that the underflooding process dominates on the city territory, at that the hydrogeological nature of the prevalent hazardous geological processes is characteristic for the alluvial complex.

DISCUSSION

The methods for calculating the proposed indicators are fully consistent with recommendations on the development and quality of so-called SMART indicators compatible with sustainable development: specific, measurable, ambitious, realistic, timebound (Maxwell, 2015). The development of the engineering geological zoning methods was initiated by the Moscow Government department which differs from the foreign methods which are initially targeted at the development of information support for the full spectrum of urban planning tasks (Mulder, 2001, Culshaw, 2009, Pereyra, 2003, Busha, 2019). Although in the 21st century with technological development and the proclaimed thesis "you can build everywhere", the destination of the obtained results should be considered from the position of the city economy. Information about the distribution of dangerous geological processes is important for municipal services: operation of buildings and engineering structures, drainage systems, planting greenery and forest and parks, specially protected natural areas, cultural heritage sites, cemeteries, etc. Unfortunately, until present, these issues are not adequately addressed in the Moscow city planning methods, though according to the normative-technical documentation regulating the operation municipal services and facilities[4], an increase in the maintenance expense is considered in those cases when the object is located in a hazardous geological process zone (for example, normative periodicity of inspection of building – 1 time in 10 years, however, if the building is located in the hazardous geological process zone – in 5 years).

An analysis of international project GeoInforM and last project of The Federal Service for State Registration, Cadaster and Cartography reveals that the implementation of urban planning methods with due account for the geological environment features is most efficient on the basis of the unified city digital platform and development of "open data" for the municipal community and population[5].

The Russian approach makes it possible to solve the tasks of protection and rational use of the geological environment as a part of the large-scale engineering geological zoning of the city territory on condition of development of the city Geological Fund of the geological engineering surveying in terms of supplementing data of the engineering geodetic monitoring of the geological processes and geotechnical monitoring of buildings, engineering structures and ground surface (75 years, 2019).

The proposed approach is aimed at resolution of the problems facing the system of spatial planning, first of all in the part of development of geoecological aspects of the regional model for the territorial planning of the urbanized territories. The proposed approach is focused on solving the problems facing the system of territorial planning, primarily in terms of developing geoecological aspects of the regional model of territorial planning of urbanized territories.

[4] Interstate standard 53778-2010 (2010) "Buildings and Structures. Rules of Inspection and Monitoring of Technical Condition" – the electronic resource of the legal reference system ConsultantPlus https://www.consultant.ru/online/(in Russian),

[5] Spatial Data: the Needs of the Economy in the Context of Digitalization / E. Belogurova, V. Vorobyev, O. Gvozdev et al.; The Federal Service for State Registration, Cadastre and Cartography; National Research University Higher School of Economics; Institute for Scientific Research of Aerospace Monitoring "AEROCOSMOS". – Moscow: HSE, 2020. ISBN 978-5-7598-2152-6 (in Russian)

CONCLUSIONS

The developed methods allowed to define meaningful provisions for the urban planning of Moscow territory:

- The feasibility of using the hierarchical system of taxa of the structural-geomorphological complexes based on the engineering geological zoning,
- Special importance of the endogenous factors in the geoecological properties of the city territory,
- Need to take into account the surface runoff accumulation zones as a part of the geomorphometric indicators,
- The substantiated set of the geomorphometric indicators sufficiently describes the landscape properties,
- Differences and similarity of distribution of the geomorphometric indicators by taxa between the structural-geomorphological complexes,
- The predominance of the hydrogeological nature of the vulnerability of taxa from exogenous processes,
- Need to develop digitalisation and use of the open data in the urban planning system and especially in the part of the environmental management.

Implementation of the proposed approach on the example of Moscow territory brings closer to development "geoecological image" of the city, giving particular importance to the endogenous factors when defining the structural-geomorphological complexes and allowing to obtain and compare quantitative evaluations of the main geoecological properties based on the accounting the exogenous processes manifestations.

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