The Geological Structure Style of Karst Massive in the Karst Susceptibility Assessment

Elena V. Drobinina[1(✉)], Tatyana G. Kovaleva[2], Denis R. Zolotarev[1], and Valerii N. Kataev[2]

[1] Laboratory of Prognostic Modeling in Geosystems, Perm State University (PSU), LLC «Karst-Control and Bank Protection», Perm, Russia

[2] Faculty of Geology, Perm State University (PSU), LLC «Karst-Control and Bank Protection», Perm, Russia

Abstract. The integral karst susceptibility assessment is very informative from a prognostic perspective for areas where soluble rocks are overlaid by insoluble ones. It takes into account not only the surface and subsurface karst forms distribution, but the indicators of the geological structure, such as tectonic, geological, hydrogeological, geomorphological factors that control the karst process development. The geological structure style of karst massive in this assessment is considered by research of influence of the zone of weakness in karst massive on the geotechnical properties of the overlaying soils. The results of this research was applied for making of integrated susceptibility model (map). The karst susceptibility model that is made using analysis of common geological structure parameters was complemented by the model that based on a complex assessment of the overlaying soil geotechnical properties. The results of this investigation show the effectiveness of the research of the karst massive geological structure style in order to the karst susceptibility assessment.

Keywords: Integral karst susceptibility assessment · Karst massive · Geotechnical properties

1 Introduction

The study of overlying soils is due to the wide distribution of soluble rocks overlaid by a stratum of insoluble deposits, which prevents direct observation of the karst process development.

A practical interest for planning or engineering purposes requires quantitative sinkhole susceptibility assessments which include two components: the probability of sinkholes occurrence and their sizes at the time of formation, which is «a critical engineering design parameter» [8]. A lack of information about karst occurrences such as sinkholes, karst cavities and their distribution specifies the difficulty of the assessment of the probability of collapse sinkholes formation, which is characterized by a suddenness and social, economic or environmental damage.

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Within the Russian Federation, large sinkhole forms associated with the development of sulfate (gypsum, [7]), carbonate-sulfate (carbonate-gypsum, [7]) types of karst, which are found on the territory of the Central European part and in Urals. The key feature of sulfate karst is the high rate of fractured gypsum and anhydrite dissolution. So, large karst cavities can form under a thick stratum of insoluble water-resistant overlying soils as a result of the sulfate dissolution by aggressive waters. Enormous collapse sinkholes can form as a result of collapsing caves or karst cavities that formed within the gypsum and anhydrite bedrock and reached critical sizes [11].

Karst structures can be analyzed by different geophysical methods, especially geophysical tomography methods that are largely used now for determining the depression and cavity areas filled with alluviums, gypsum clasts, and water. These methods are wildly reported [17] Geophysical methods such as ground penetrating radar (GPR) that are the most resolute method, seismic reflection (SR) and electrical resistivity tomography (ERT) were applied to locate the main karst cavities and caves [15]. For example, the shape and the distribution of subsurface karst forms underneath the Neogene and Quaternary sediments was determined by geophysical methods in the territory of distribution of karst fields in Yugoslavia [16]. In this research, karst structures are analyzed by study of the geological structure style of karst massive.

Conceptually, this study is based on the idea that despite the suddenness of the sinkhole formation, the karst susceptibility assessment can be carried out using data of geological structure style of karst massive such as tectonic, geological, hydrogeological, geomorphological factors and etc.

The integral karst susceptibility assessment is very informative from a prognostic perspective for areas where soluble rocks are overlaid by insoluble ones [10, 12–14, 21, 23]. The integral karst susceptibility assessment takes into account not only the surface and subsurface karst forms distribution, but the indicators of the geological structure (environmental factors), that control the karst process development.

2 Short Characteristics of the Research Area

The research region is situated in the southeast of the Perm region, Russia (Fig. 1). It is located in predominantly gypsum and carbonate-gypsum karst area of the Kishert district [7]. The study area is located within the territory of Ust-Kishert village on the second accumulative terrace of the Sylva river.

The geological characteristic of research area are represented by authors early [3]. The Kishert karst region extends in a narrow strip along the eastern slope of the Ufa plateau from the Sylva and Shakva watershed to the southern border of the Perm Territory. Geologically, the area is located in a narrow junction zone between the East European platform and the Ural mountains. The soluble rocks are typified by the Artinskian stage and the Filippovsky and Irensky horizons of the Kungurian stage of the Permian system. They are overlaid by Neogene-Quaternary karst-collapsed debris, Quaternary alluvium and diluvium.

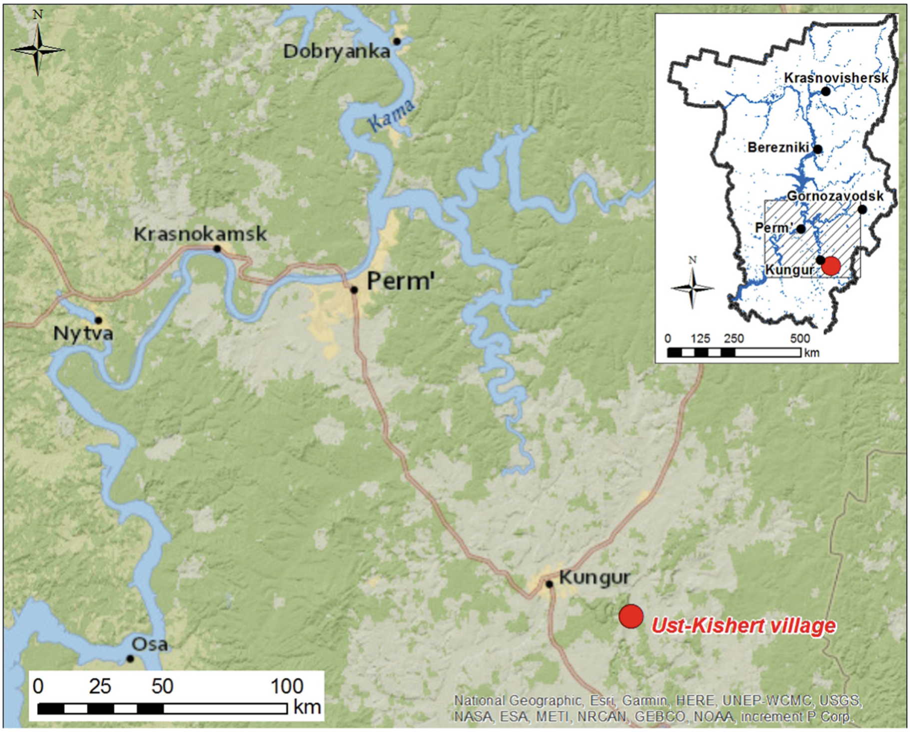

Fig. 1. The location of the research area in Perm region territory

Karst forms which are spread in the research area were identified by digitizing topographic maps (sinkholes), analyzing drilling results (karst cavities) and data of archival karstological research that are carried out in the area by Perm State University (both sinkholes and karst cavities). In addition, the sinkholes are mapped on sensing data such as satellite images.

The remote sensing data is often used to detect the karst forms distribution. For example Brinkmann R. et al. [2] used for the same purpose aerial photographs from 1926 and 1995 that covered the urbanized Pinellas County, Florida, USA. Nowadays multidate aerial photographs are frequently used for purposes of the karst features measurement. Basso and al. [1] on the go of morphometric analysis of sinkholes in a karst coastal area used the oldest photos, dating back to the 1940s and 1950s, with aim to identify sinkholes that are at present partly or entirely covered by urbanized areas, or that have been filled over time.

According to observations survey by scientists of Perm State University, 120 surface karst forms, 60 karst cavities and 24 crushed zones are fixed within Ust-Kishert village [3, 4]. Sinkholes are frequently called dolines in scientific literature [5, 6, 16, 22], but in this research sinkholes are any surface enclosed depression form which are karst related.

3 Research Methodology

The geological structure style of karst massive in the karst susceptibility assessment is studied by research of influence of the zone of weakness in karst massive on the geotechnical properties of the overlying soils. The zones of weakness in karst massive are areas where massive structure is disturbed by solution or fissure tectonics or gravity collapse. In the research Neogene-Quaternary karst-collapsed debris zone takes on the role of the zone of weakness in karst massive. This zone consist of karst-collapsed debris and fine-grained products of weathering between them. Obviously, due to the filling of the fissure-cavity space with fine-grained material, the influence of this zone of weakness can be relatively weaker than the influence of open cracks, fissures and karst cavities. The thickness of Neogene-Quaternary karst-collapsed debris zone within the research area on the second accumulative terrace of Sylva river varies from 10 to 40 m, with an average value of 20–25 m.

The distribution of the surface and subsurface karst forms within the different classes of the thickness values of Neogene-Quaternary karst-collapsed debris are represented in the Fig. 2. The histograms was made using databases which are made for the territory of Ust-Kishert village [12–14].

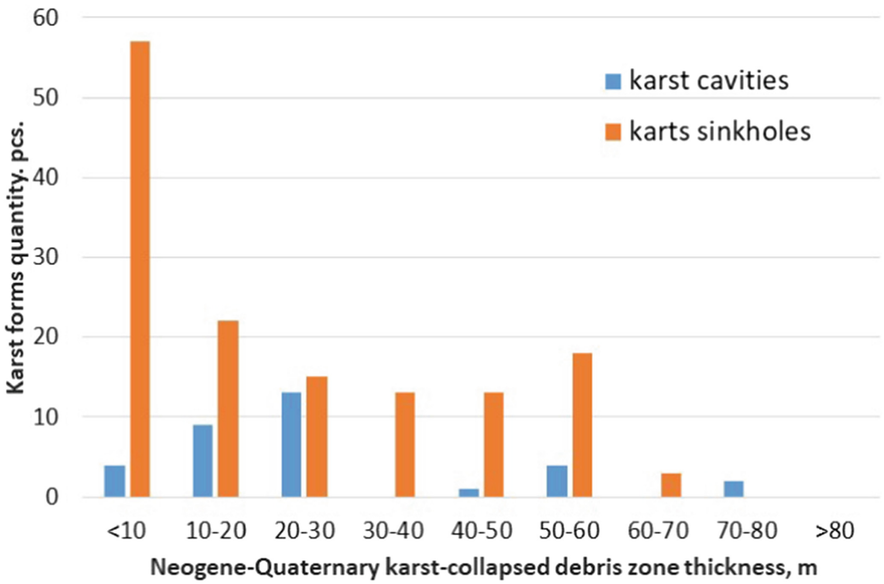

Fig. 2. Distribution of the surface and subsurface karst forms within the different classes of thickness values of Neogene-Quaternary karst-collapsed debris [12–14]

The majority of karst forms are widespread on the territory where the thickness of Neogene-Quaternary karst-collapsed debris zone is the first tens of meters: up to 20–30 m (for karst cavities) and up to 50–60 m for sinkholes.

The influence of the zone of weakness in karst massive on the geotechnical properties of the overlying soils is studied by determining *the degree* and *nature* of this influence, which characterized by the distance from the zone of weakness. The distance is calculated as the vertical interval from the research soil sample to the top of the Neogene-Quaternary karst-collapsed debris zone, marked early as the zone of weakness in karst massive. The statistical data analysis is applied in the research.

The use of the statistics in the karst susceptibility assessment is highlighted in the work of German scientists [18]. The authors proposed two methods of the engineering-geological assessment of karst susceptibility: *the interaction analysis* and *the orientation analysis*, based on the use of a mathematical and statistical apparatus. The first method is based on the search for the interaction parameters of surface forms (sinkholes): the radius and strength of interaction which can be used as inner parameters in mapping. A map is similar to the map of the distance from karst forms [20], on which potentially dangerous zones are located within the radius of interaction of karst sinkholes that calculated using mathematical-statistical methods. The second method is based on the search for the main directions of tectonic faults using orientation of karst forms as predicted directions of potential sinkhole formation. It is believed that the most karst dangerous zones are controlled by fracturing.

In this research the geotechnical properties of Upper quaternary loams, predominantly hard-plastic and semi-hard, heavy are studied in the statistical data analysis. To determine *the degree* of the influence, which characterized by the distance from the zone of weakness, one-dimension analysis of variance was used, a detailed description of which is widely covered in the reference literature [19].

The nature of the geotechnical properties variability due to the distance from the zone of weakness was evaluated by direct comparison of standardize values of geotechnical properties and the vertical interval from the research soil sample to the zone of weakness. The scatter plots, which characterize their dependence, are made. Obviously, the diagrams, which shown in Fig. 3A are not informative and it is impossible to establish an approximate nature of the relationship using it. Determining the lines of best fit by averaging the geotechnical properties values within the limits of regular intervals of the distance values allows extracting of information about the nature of the dependence (Fig. 3B). This procedure can help to assess the direction of the dependence (trend), and, in some cases, to establish its nature (linear, exponential, lognormal, etc.).

A significant influence of the Neogene-Quaternary karst-collapsed debris zone on the geotechnical properties of Upper quaternary loams was determined. This study has found that generally density of loam and their cohesion increase as the distance from the zone of weakness increases, too. Conversely, the values of the porosity coefficient decrease. The results of this investigation was applied for making of integrated susceptibility map.

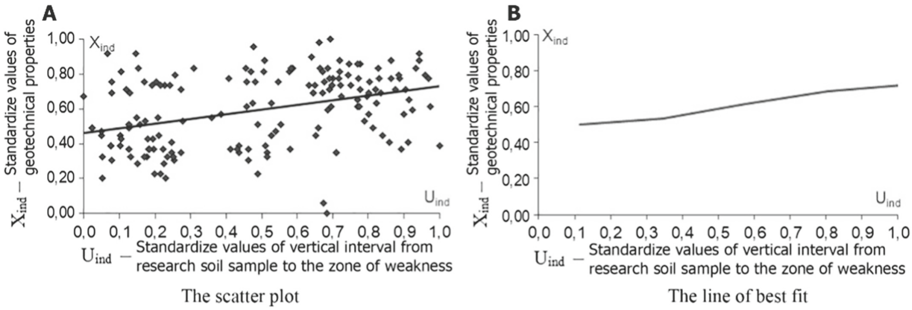

Fig. 3. Scatter plots of nature of geotechnical properties variability due to distance from zone of weakness

4 Integrated Susceptibility Map

According to [9] there are two types of predictive model of sinkhole formation: hazard models and susceptibility models. The hazard models represent quantitative probability estimation for a given zone and time interval of being affected by a sinkhole event. The relative probability of a sinkhole occurring in any specific place is provided by *susceptibility* models [3].

The method of creating an integral map of karst susceptibility is reduced to the mapping of particular raster models of the investigated properties (density of loam, cohesion and porosity). Then they are conversed into a score model according to the principle of increasing the susceptibility score as the density and cohesion decrease. Afterwards the score models have to be combined and scores have to be sum.

Particular raster models are made by interpolation of geotechnical properties, which are determined on samples from the bottom of Upper quaternary loams where the influence of the zone of weakness is the biggest. Then the raster models are classified by the method of geometric intervals (Geometrical Interval), which makes it possible to achieve approximately the same number of values in each class and the sizes of the intervals will be approximately equal.

The classified raster models is reclassified into score ones. It means that ranges of real values are changed into scores according to results of previous research, which is shown in Sect. 3. The maximum score of karst susceptibility is assigned to the intervals of the minimum values of density and cohesion, and to the intervals of the maximum ones of porosity coefficient.

A result of the score models combination is the integrated susceptibility map, on which the study area is ranked into classes of different karst susceptibility: from low to the highest. The low susceptibility fits to the territory where the total susceptibility score is less than five, the highest susceptibility fits to the territory where the total susceptibility score is more than ten. The territory with intermediate values of karst susceptibility is divided into two categories. Thus, for the study area, an integrated karst susceptibility map was made in respect of the variability of the geotechnical properties of the studied overplaying soils (Fig. 4).

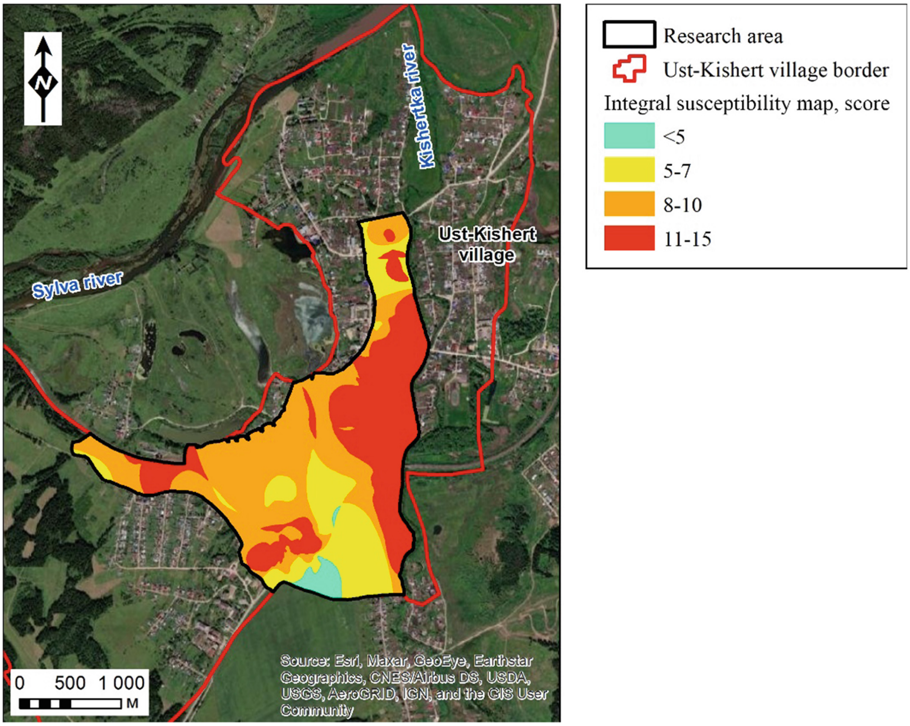

Fig. 4. Integral karst susceptibility map for area of second accumulative terrace of Sylva river (map projection: EPSG: 3857 Mercator Auxiliary Sphere)

Verification of the integral karst susceptibility map is carried out by analyzing of a space relapse of the karst forms location due to different categories of karst susceptibility. The result of the spatial analysis is presented in tabular (Table 1) and graphical (Fig. 5) form, which indicate the quantity of karst forms related to the categories on the integral model. The maximum quantity of karst forms is noted within the category of the highest karst susceptibility, while the low karst susceptibility category is characterized by the absence of subsurface forms and a minimum quantity of surface ones.

The second way of the verification this map is visually comparison it with the karst susceptibility model developed by T.G. Kovaleva early, who made it using analysis of common geological structure parameters ([14], Fig. 5). First, it is necessary to analyze geological, karstological and other data towards to identify the regularities of the spatial relationship of the geological and hydrogeological environment indicators and surface and subsurface karst forms. It is necessary to select the most significant indicators for research area due to its geological and hydrogeological structure and its influence on the development of karst process. These indicators can be grouped into main groups: the thickness and bedding of soluble rocks, the thickness and bedding of overlaying soils and hydrogeological parameters.

Table 1. Quantitative assessment of karst susceptibility within the different categories.

Karst susceptibility category and its quality characteristic		Integral score	Karst forms quantity		
			Crushed zones	Kars cavities	Sinkholes
1	Low	<5	0	0	2
2	Medium	5–7	3	6	3
3	High	8–10	5	8	7
4	The highest	11–15	4	18	7

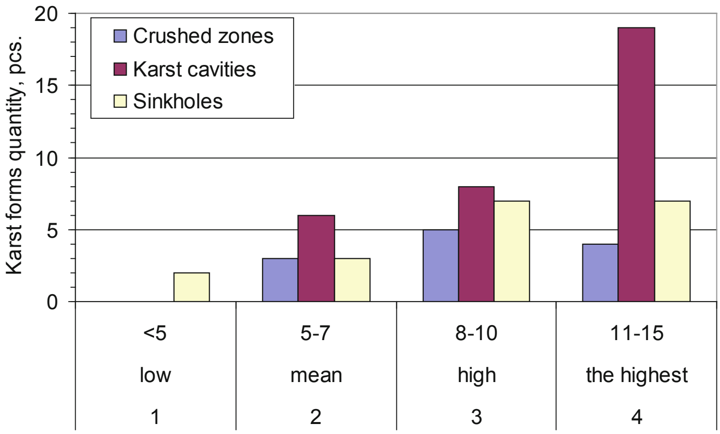

Fig. 5. Distribution of the surface and subsurface karst forms within the different categories

Then, the selected indicators are analyzed and the most karst dangerous intervals of their values are identified. The most karst dangerous intervals is a range of indicators intervals values, which characterizes the most values of karst forms. There are three intervals of the indicators: «dangerous», «quite dangerous» and «not dangerous». The boundaries between intervals are established by a sharp decrease (or increase) the quantity of karst forms (or their size). The greatest quantity of karst forms «falls» within the limits of the dangerous interval. If there are several maximums of the quantity karst forms, according to the values of the studied indicators (heterogeneity of distribution), two or more intervals of «dangerous values» can be distinguished [14].

There are a few numbers of selected indicators which analyzed for research area of Ust-Kishert village. So, their hierarchical subordination is not established and all indicators are considered as equivalent [13] (Fig. 6).

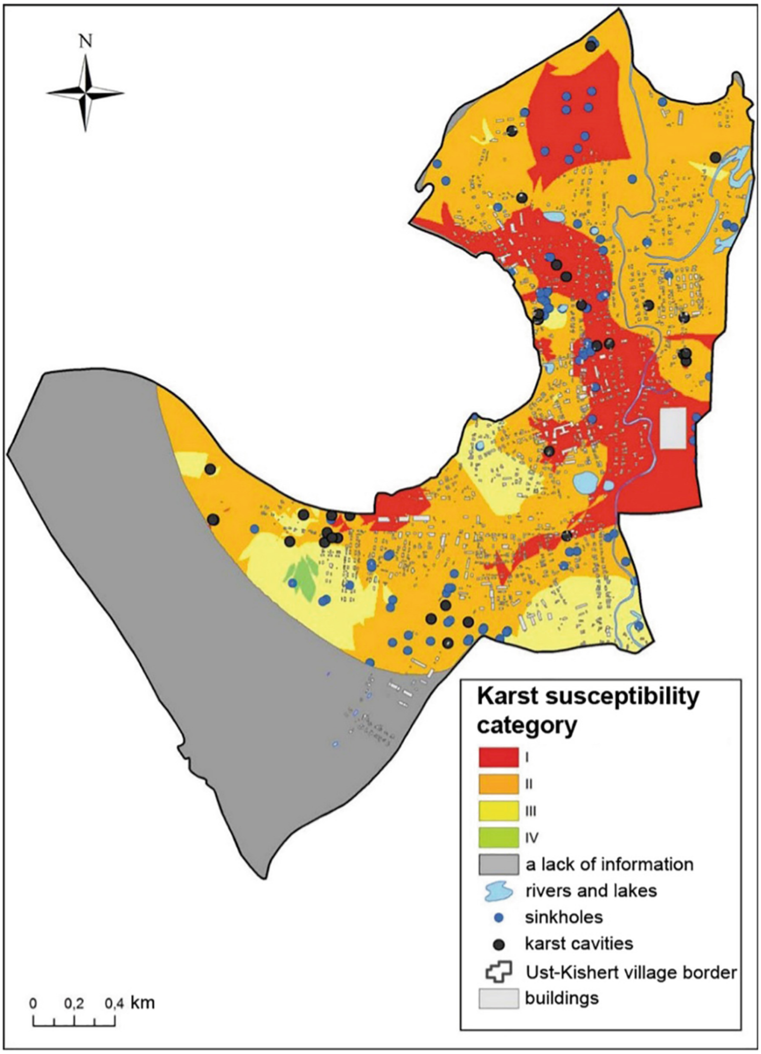

Fig. 6. Integral karst susceptibility map for area of Ust-Kishert village (map projection: EPSG: 28410 Pulkovo 1942/Gauss-Kruger zone 10; [13])

A very dangerous (I) category of karst susceptibility on the territory of Ust-Kishert village occupies 1.05 km^2 of area in the northern and eastern parts of the village. Almost 30% of surface and more than 20% of subsurface karst forms are confined to these areas, and their average sizes are larger than the average sizes of karst forms that are located in areas of different categories of karst susceptibility. The largest area (41.5%) is occupied by the dangerous (II) category, within which most of the sinkholes and karst cavities are concentrated. The quite dangerous (III) category (9.29%) is localized in the south and central part of the village, as well as on the border with the territory that is not covered by studies, occupied more than 30% of the area of the village and located in the southwestern its border. The smallest area is occupied by a potentially dangerous (IV) category (0.32%). Within its limits no karst forms have been recorded.

For perception convenience of visual comparison, the authors has superimposed the developed cartographic model (model 2) on the model of karst susceptibility by T.G. Kovaleva (model 1, [14], Fig. 7).

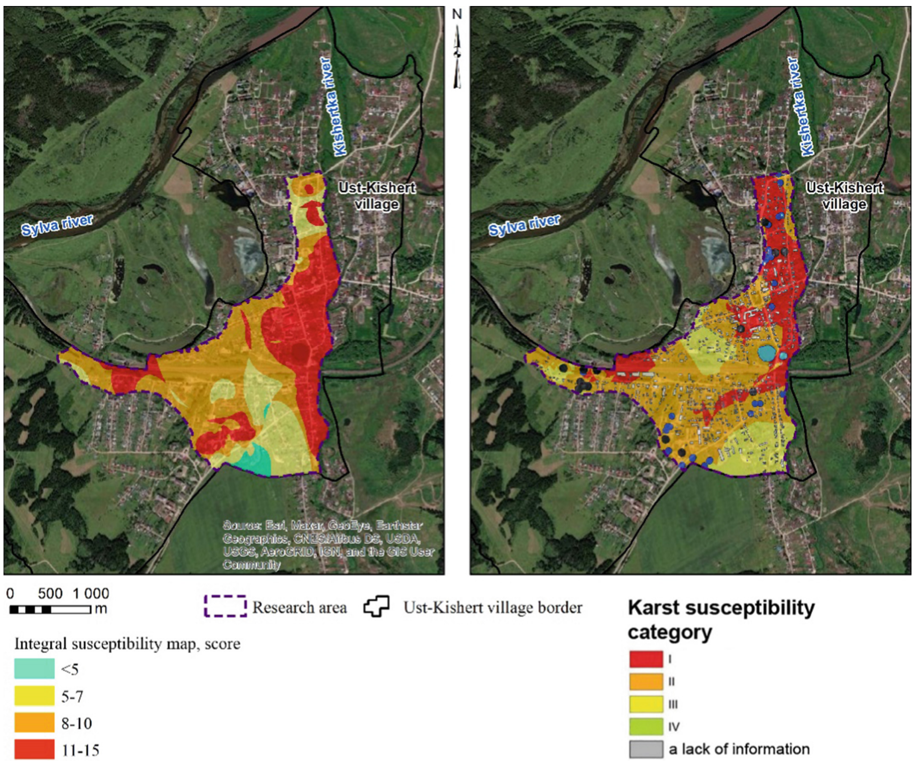

Fig. 7. Integral karst susceptibility maps for area of second accumulative terrace of Sylva river (map projection: EPSG:3857 Mercator Auxiliary Sphere)

Figure 7 shows that the compared models are characterized by significant similarity: most of the area is described by the highest and high karst susceptibility categories (model 2; 8–10 and 11–15 points, respectively) and very dangerous and dangerous (I and II) ones (model 1), which mostly coincide spatially, apart from a few sections. The southern part of the study area on model 2 is characterized by low and medium karst susceptibility categories (<5 and 5–7 points, respectively), while in the south of the area on model 1 there are territories of quit dangerous and dangerous categories (II and III). Also, model 2 shows an area of the highest karst susceptibility (11–15 points) in the southeast of the study area, where on model 1 this area is dangerous (II).

The visual similarity is confirmed by the result of these models convergence such as the spatial relationship of the models through their intersection. The percentage convergence ratio is calculated as the ratio of the area occupied by a category from model 2 within areas of a similar category on model 1 to the total area occupied by this category (model 2; Table 2).

Table 2 shows that low category on the model 2 fits to III category on the model 1 (74%), medium one fits to II and III categories (46% and 35%), high one fits to II category (67%), the highest one fits to II and I categories (39% and 55%).

Table 2. The models convergence percentage matrix.

Model 1		Model 2				Sum
		Karst susceptibility category				
Integral score	Karst susceptibility category	I	II	III	IV	
<5	Low	0%	26%	74%	–	100%
5–7	Medium	19%	46%	35%	–	100%
8–10	High	16%	67%	17%	–	100%
11–15	The highest	55%	39%	6%	–	100%
<5	Low	0%	26%	74%	–	100%

5 Conclusions

The experience in the study of karst massive shows that a karstological forecast has to take into account the geological structure style of karst massive that determine the karst process development and the nature of its forms. It is necessary to study not only the intensity of sinkhole formation and their average diameters, but also general geological conditions, which include geotechnical properties of overlying sediments.

In the research the karst susceptibility model, that is made using analysis of common geological structure parameters, was complemented by the model, that based on a complex assessment of the overlying soil geotechnical properties. These models have good convergence of results and complement each other.

The results of this investigation show the effectiveness of the research of the geological structure style of karst massive in order to the karst susceptibility assessment. The karst susceptibility model can be used to identify karst dangerous areas above the zone of weakness in the karst massive.

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