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Scientific assessment of negative changes in the state of karst groundwater

Evaluación científica de los cambios negativos en el estado del agua subterránea karst

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ABSTRACT

Centralized water supply in remote settlements is often difficult or impossible, so there is a need to use a non-centralized water supply. The article develops a method for an expert assessment of the negative change in the state of underground karst waters based on a paired analysis of complex indicators of the protection of the aquifer. To assess the vulnerability of non-centralized water supply sources, five factors are used, including the geological structure of the territory, the level of surface and underground runoff, the development of the karst network, precipitation regime electrical conductivity, and mineralization of groundwater. The test was performed using the method of inversely weighted distances (IDW). The vulnerability assessment of karst waters was carried out in the area of 10 key control points identified during the deployment of the hydrogeological control system in 2017. Based on various geological and hydrological indicators, the discrepancy between the vulnerability assessment of karst waters was no more than 15 %. The conditions under which it is advisable to use direct measurements or geoelectric methods to monitor karst groundwater's state are identified.

Keywords: Karst Water Vulnerability Assessment; Non-Centralized Water Supply; Geoelectric Method; Karst Processes.

RESUMEN

El suministro de agua centralizado en asentamientos remotos suele ser difícil o imposible, por lo que es necesario utilizar un suministro de agua no centralizado. El artículo desarrolla un método para una evaluación experta del cambio negativo en el estado de las aguas kársticas subterráneas basado en un análisis par de indicadores complejos de la protección del acuífero. Para evaluar la vulnerabilidad de las fuentes de abastecimiento de agua no centralizado, se utiliza un conjunto de cinco factores, que incluyen la estructura geológica del territorio, el nivel de escorrentía superficial y subterránea, el desarrollo de la red kárstica, el régimen de precipitaciones, la conductividad eléctrica y mineralización de las aguas subterráneas. La prueba se realizó utilizando el método de distancias inversamente ponderadas (IDW). La evaluación de la vulnerabilidad de las aguas kársticas se llevó a cabo en el área de 10 puntos de control clave identificados durante el despliegue del sistema de control hidrogeológico en 2017. Con base en varios indicadores geológicos e hidrológicos, la discrepancia entre la evaluación de la vulnerabilidad de las aguas kársticas fue de no más de 15 %. Se identifican las condiciones bajo las cuales es recomendable utilizar mediciones directas o métodos geoeléctricos para monitorear el estado de las aguas subterráneas kársticas.

Palabras clave: Evaluación de la Vulnerabilidad del Agua Karst; Abastecimiento de agua no centralizado; método geoeléctrico; Procesos kársticos.

1. INTRODUCTION

In many cases, the use of a non-centralized water supply in remote settlements is the only possible option. Reliable provision of high-quality water supply to the population of such territories is an urgent task, especially in the presence of active karst processes. Karst groundwater is the only freshwater resource for many regions and cities around the world (Romanov et al., 2022). However, karst water exchange systems have a high natural and anthropogenic vulnerability of groundwater and a low ability to self-purify from pollutants (Drew & Hötzl, 1999). One of these regions is the Nizhny Novgorod region (the territory of the Oka River karst) (Tolmachev et al., 1986; Dorofeev et al., 2016). Feeding of the aquifer and many rivers of this area (the Oka River, the Tesh River, the Serezha River, the Bol River. Kutra), are formed mainly from sources of karst origin and precipitation. In addition, the water supply of large settlements is based on the use of these sources.

Currently, many different methods and approaches for assessing the vulnerability of groundwater have been developed (Vrba & Zaporozec, 1994; Ford & Williams, 2007; Klimchuk, 2008), which are based on hydrogeological zoning methods, index-rating, and parametric methods, etc. In most countries with a significant share of karst territories, the regulatory documents have introduced differentiation of approaches to protecting groundwater and water intakes in karst-type reservoirs and the most appropriate ones to their individual hydrodynamic characteristics applied. The European Commission has created a European approach to assessing the vulnerability of groundwater in karst conditions in certain regions, Cost action 620 (Zwahlen, 2004; Chen et al., 2021). The report of the COST of Action 620 program formulated a methodology for mapping the vulnerability of underground waters of karst origin. This methodology evaluates the protective properties of soils and overlapping layers of karst and non-karst rocks, the concentration of runoff entering karst channels, and the precipitation regime. Additionally, the development of the karst network is taken into account. On the basis of this methodology, partial methods of vulnerability assessment of karst underground waters are developed (Tokarev, 2018; Tokarev & Klimchuk, 2014).

To assess the quality of karst waters in the territories of non-centralized water supply, it is necessary to use complex methods and approaches for hydrogeological control of the territory in the conditions of karst formation. Estimates should be based on the processing of heterogeneous spatial geological and hydrogeological data and operational information from local observation systems. Spatial indicators can characterize the spheres of influence of various factors on the vulnerability of underground karst waters, depending on the conditions of interaction with users and the conditions of mutual influence (Sharapov & Kuzichkin, 2013; Stevanović & Stevanović, 2021).

The aim of the work is to develop a methodology for an expert assessment of the negative change in the state of underground karst waters based on a pair analysis of complex indicators of the protection of the aquifer.

2. METHODOLOGY

Due to regional climatic, hydrogeological, and landscape features, it is advisable to develop specific methods for assessing the protection of karst underground waters (Maksimovich, 1963; Kuzichkin et al., 2020; Dorofeev et al., 2016). To assess the vulnerability of sources of non-centralized water supply, a factor O is taken into account, including such indicators as lithology, soil thickness, the presence of a karst base. The most intensive karst processes occur on river terraces valley slopes. Factor C includes the level of river flow through hydrogeological posts, underground flow, karst craters, tectonic faults and vegetation. The development of karst is also facilitated by high gradients of underground flow and groundwater outlets in riverbeds and coastal slopes. To do this, factor K is taken into account, which is a criterion of the development of the karst network and the hydrographic network. The hydrographic network is characterized by the density of the river and valley network. The density of the river network of the karst area can be determined in accordance with the known method (Vías et al., 2006), based on the following ratio:

$$K_R = \frac{\Sigma L}{F} \tag{1}$$

where ΣL is the length of all rivers in linear kilometers, including temporary drying watercourses; F is the area of the studied territory in km^2.

A relatively large amount of precipitation, especially in the form of rain, and low evaporation, determine the increased values of surface and underground runoff, the greater intensity of water exchange and water circulation in the near-surface horizons of rocks, and, accordingly, the development of dissolution and leaching processes. The P factor takes into account the amount of liquid and solid sediments involved in feeding karst waters.

Among the external factors, the solubility of minerals is significantly affected by the total mineralization and chemical composition of the dissolving waters. The L factor characterizes karst groundwater's electrical conductivity, mineralization, and temperature. Hydrogeochemical assessment of the karst process development intensity is carried out according to the degree of groundwater aggressiveness in relation to karst rocks, i.e. the amount of water-soluble rock that can transform into solution the amount of water-soluble rock carried out by groundwater from a unit area.

Based on these factors, an expert assessment is formed, which can be obtained using pair analysis (Romanov et al., 2015; Romanov et al., 2020). For this purpose, a matrix of factors is built, according to which the possible vulnerability of sources of non-centralized water supply is estimated. This technique can be built on the basis of an interval estimation, which allows using sample data to find a two-sided interval in which the true but unknown value of the rank of the distribution parameter lies within a given probability. The confidence probability is set a priori 95% based on regulatory requirements. The boundaries of the confidence interval are:

$$\overline{x} - g\frac{\sigma}{\sqrt{n}} \le \mu \le \overline{x} + g\frac{\sigma}{\sqrt{n}} \tag{2}$$

where μ is the mean value of the factor rating; $\overline{x}$ is the sample average, which contains μ; σ is the standard deviation from the average; g is tabulated p-value significance level (may be found in the Laplace function table); n is the number of elements in the sample.

Based on the interval indicators, tables with ratings are formed, according to which preliminary estimates and a vulnerability assessment matrix are determined. The ratings for each factor are presented below (Figure 1):

$O = \{O_L, O_M, O_K\}$

Lithology O_L	Rating
Clays	9
Loam	8
Marls	6
Sandstones, gravel	3
Karst rocks	1
Open karst sinkholes	0

Soil capacity O_M, м	Clay, rating	Sandy, rating
>1,2	9	6
0,3-0,7	6	3
0,1-0,3	3	1
≤0,1	1	0

Thickness of the overkarst base O_K, м	Rating
>10	6
5-10	3
<5	0

$C = \{C_Q, C_d, C_K\}$

Average annual river flow C_Q м³/c	Rating
>1000	9
100-1000	7
25-100	5
5-25	2
<5	0

Number of sinkholes per km² C_d	Depth of a sinkhole, m	Rating
>40	>20	9
20-40	10-20	7
5-20	5-10	5
0-5	<5	2

Vegetation cover, C_K		
Slope %	Density	Rare
<8	1	0,8
8-31	0,8	0,7
>31	0,7	0,6

$K = \{K_P, K_t, K_R\}$

Permeability K_p	Rating
Channel	1
Transitional	3
Fractured	6

Time to reach the exit (day))K_t	Rating
≤1	1
1-10	3
>10	6

Density of the hydrographic network K_R km / km²	Rating
>0,4	9
0,3-0,4	7
0,2-0,3	6
0,1-0,2	3
0-0,1	1

P

Average precipitation P, mm	Rating
>600	6
500-600	4
400-500	2
<400	1

$L = \{L_M, L_L\}$

Mineralization L_M mg/l	Electrical conductivity L_L mSm/cm	Rating
>1,2	>1,2	9
0.6-1,2	0,8-1	6
0,3-0,5	0,4-0,7	3
<0,3	<0,4	1

Figure 1. Rating assessments of vulnerability factors of non-centralized water supply sources

In the vulnerability assessment matrix W, the conditions for the formation of the evaluation coefficients of the ratings $a_{i,j}$ are set based on the comparison of the average ratings:

$$a_{i,j} = \begin{cases} 1, \Phi_i \cong \Phi_j - \text{factors are equally important} \\ 2, \Phi_i \geq \Phi_j - \text{one factor is more important than the other} \\ 3, \Phi_i > \Phi_j - \text{one factor is much more important than the other} \\ 4, \Phi_i \text{»} \Phi_j - \text{one factor is absolutely more important than the other} \end{cases} \quad (3)$$

The matrix will be inversely symmetric; the matrix elements located below the diagonal are inverse with respect to the base elements.

$$W = \begin{vmatrix} 1 & a_{1,2} & a_{1,3} & a_{1,4} & a_{1,5} \\ 5 - a_{2,1} & 1 & a_{2,3} & a_{2,4} & a_{2,5} \\ 5 - a_{3,1} & 5 - a_{3,2} & 1 & a_{3,4} & a_{3,5} \\ 5 - a_{4,1} & 5 - a_{4,2} & 5 - a_{4,3} & 1 & a_{4,5} \\ 5 - a_{5,1} & 5 - a_{5,2} & 5 - a_{5,3} & 5 - a_{5,4} & 1 \end{vmatrix} \quad (4)$$

Based on the obtained vulnerability assessment matrix, the influence of heterogeneous factors on the overall assessment can be taken into account using weighting coefficients

$$\omega_i = \left(\sum_j a_{ij} - 1\right) / \left(\sum_i \sum_j a_{ij} - 5\right) \quad (5)$$

At the same time, the overall assessment for the selected factors affecting the vulnerability of groundwater in karst conditions in the selected zone and a given period of the year can be determined based on the following ratio

$$Q(T, H, L, \Delta H, \Delta L) = \omega_1 (O_L + O_M + O_K) + \omega_2 \left(C_Q + C_d + C_K\right) + \omega_3 \left(K_p + K_t + K_R\right) + \omega_4 P + \omega_5 (L_M + L_L) \quad (6)$$

where T is the season of the year; H, L are coordinates of the control zone; $\Delta H, \Delta L$ are dimensions of the control zone.

3. RESULTS AND DISCUSSION

Earlier in 2017, studies were conducted on the territory of the Chud village (Navashino district of the Nizhny Novgorod Region), which is subject to karst-suffusion processes. The newly developed hydrogeological control system based on identifying critical zones of geodynamic karstological monitoring and the use of local hydrogeological control based on geoelectric methods was used (Figure 2) (Kuzichkin et al., 2020; Bykov & Kuzichkin, 2014).

Figure 2. Layout of the main points of non-centralized water supply and a deployed hydrogeological control system

To form an expert vulnerability assessment based on the developed methodology of factor ratings in the territory of the Chud village in the Navashino district of the Nizhny Novgorod region and a comparative analysis with previously obtained data, an additional study was conducted in 2021.

3.1. Geological structure (Factor O)

The deposits of the Permian System of the Sakmar-Kazan and Urzhum tiers take part in the geological structure of the research area within the required depth of the section study (up to the depth of the regional water barrier). These rocks are overlain by Quaternary sediments and alluvium of the first and second above-floodplain terraces at the research site. The deposits are represented by dolomites, limestones, marls and clays. A significant part of the territory is subject to karst formations, which is manifested by the presence of craters, basins and lakes of karst origin (Figure 3).

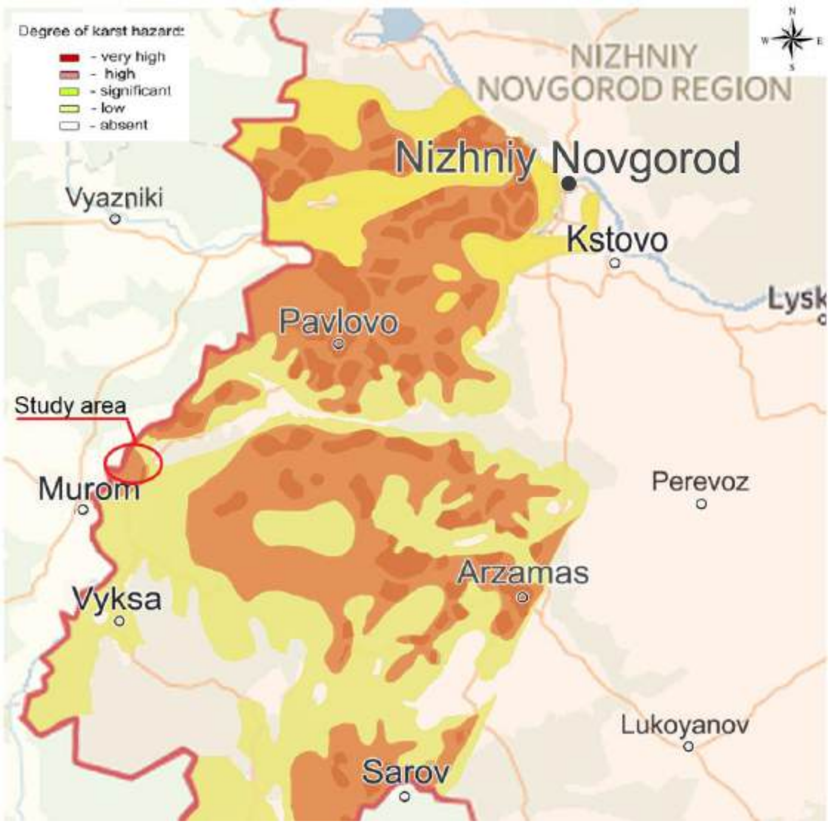

Figure 3. Geological structure of the studied territory

3.2. The level of surface and underground runoff, karst craters, tectonic faults and vegetation (Factor C)

For the territory under consideration, the average amount of runoff is stable, the flow rate for the district territory varies from 9 to 3 l/s • km^2. The annual river flow is in good agreement with the annual precipitation (Figure 4). Depending on the degree of karst formation and the degree of drainage of karst waters, deviations from the zonal value norm at different points of the same river may have different values. The discrepancy between the surface and underground catchments is most often observed in the sections of small rivers. On the Serezha and Tesha rivers, absorption is observed, and on others – the discharge of karst waters. On the Tesha and Serezha rivers, the module of the average annual runoff increases with an increase in the catchment area. With an increase in the catchment area, the influence of karst on the deviation of the annual flow rate from the zonal one decreases. For pools with an area of more than 3000 km2, the deviation of the norm from the zonal one does not exceed ± 20 %.

As part of the experimental work in 2011-2012, a karst site with an area of 0.7 sq. km was allocated, 97 karst craters with a total area of 6305 sq. m. were found on this site. The density of craters was 138 units per 1 sq. km., and the area affected by karst craters was about 90 %. The average diameter of the sinkholes was 8.1 meters, and the maximum was 20.7 meters. The distribution of sinkholes by their diameters is shown in Figure 4.

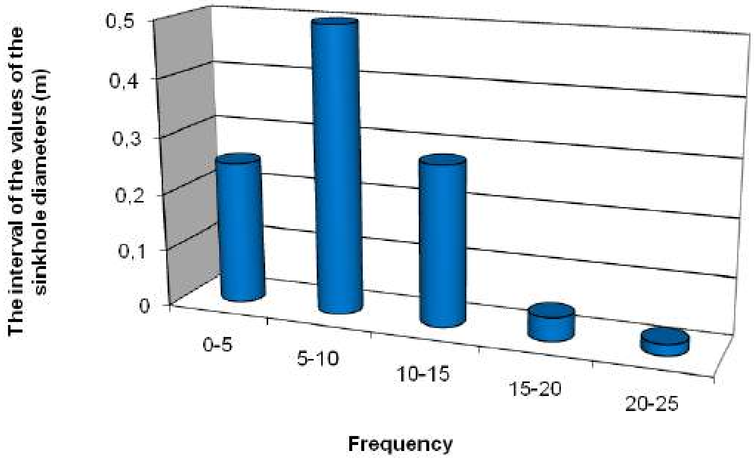

Figure 4. Histogram of the distribution of the diameters of karst craters in the study area

The vegetation of the observed territory is represented by pine-birch forests with the part of spruce and a well-developed herbaceous cover. The forest cover is 60.8 %.

3.3. The development of the karst network (factor K)

The Sakmar-Kazan sulfate-carbonate complex can be distinguished in the studied territory. It is represented by fractured marls and an aquiferous karst upper part. Near-surface zones with increased fracturing are widely represented in this territory, which is a feature of this territory. The alluvial sand deposits of the floodplain and above-floodplain terraces of the Bolshaya Kutra and Oka rivers are flooded. The water content of the horizon varies depending on the thickness of the alluvium, the granulometric composition of the water-containing sands and the degree of their clay content. The highest flow rates were observed in wells in the Oka valley from 1.94 l/s to 5.7 l/s. The average density of the river network is 0.50 km/km^2, in karst areas (the Tesha River basin) it decreases to 0.30-0.34 km/km^2.

3.4. Precipitation mode (factor P)

The horizon is fed by infiltration of atmospheric precipitation, overflow of water from other aquifers drained by the river network, as well as flood waters. Groundwater is discharged into the underlying aquifers in the absence of a water barrier between them and drainage by rivers during the low water period. According to the data for 2020, the average ascent in rivers during high rain floods is 20-180 mm/day, and the highest is up to 300-350 mm/day. The temperature of this area (Nizhny Novgorod region) averages 5.3 °C, the average annual precipitation is 683 mm. (Figure 5).

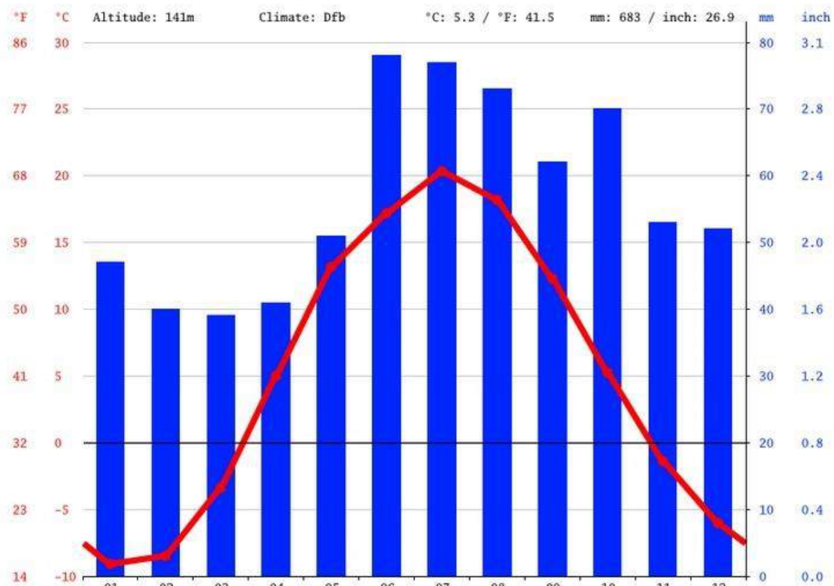

Figure 5. Average precipitation level (mm) and average air temperature for each month from Jan 01 till Dec 31, 2020

3.5. Electrical conductivity, mineralization, temperature (Factor L)

To obtain data on the electrical conductivity and mineralization of underground waters of the studied territory, from March to September 2017, regime observations were carried out at eight points using a two-pole equipotential installation (Sharapov & Kuzichkin, 2013). The data was verified by a COM 80 conductometer. The salt content and electrical conductivity were evaluated. To reduce the measurement error, the selected water samples were brought into a certain temperature range (19-21°C).

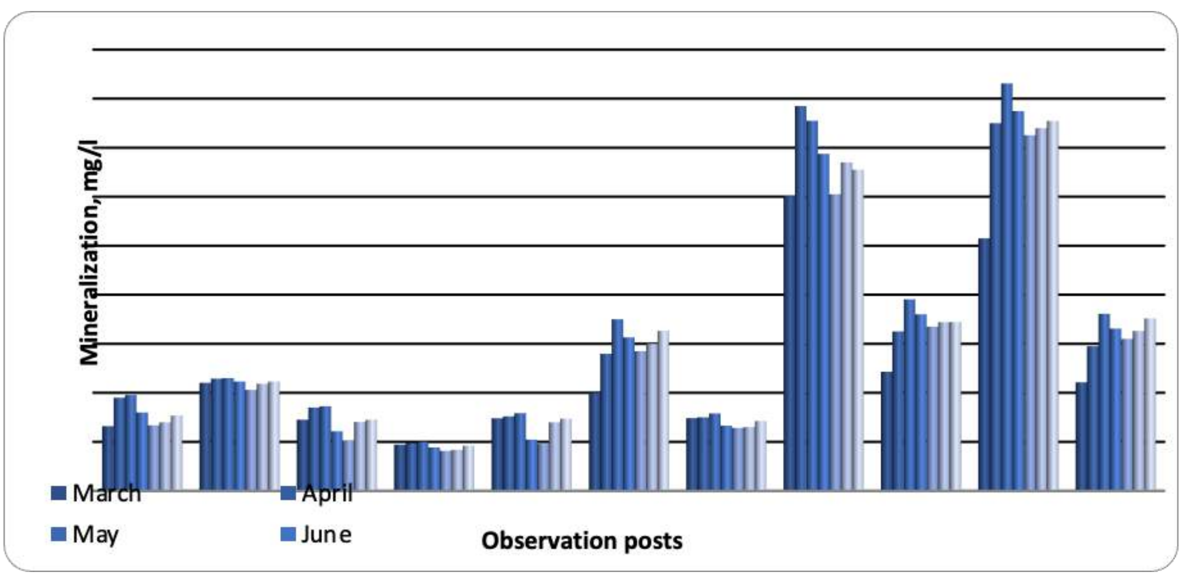

Figure 6. Results of observations on the territory of the Chud village

According to these calculations, the waters in the study area are mainly bicarbonate-sulfate, calcium-sodium and magnesium-calcium, fresh with a mineralization of 0.05-0.9 g/l, which in some places increases to 1.1-1.5 g/l due to the movement of meltwater and precipitation (Figure 6). The degree of groundwater aggressiveness in relation to karst rocks allows us to estimate the scale of karst processes development in this area.

Based on the mapping of the vulnerable territory of the Chud village, the methodology for assessing the protection of karst groundwater presented above was used (Figure 7). The vulnerability assessment of karst waters was carried out in the area of 10 key control points identified during the deployment of the hydrogeological control system in 2017, based on the developed methodology for the spring low water period. The following areas are highlighted: zones of safe drinking water use (green), zones of limited water use with a temporary restriction during spring and autumn low-water periods (yellow), zones with a critical regime for water use and the use of water only for technical needs (red).

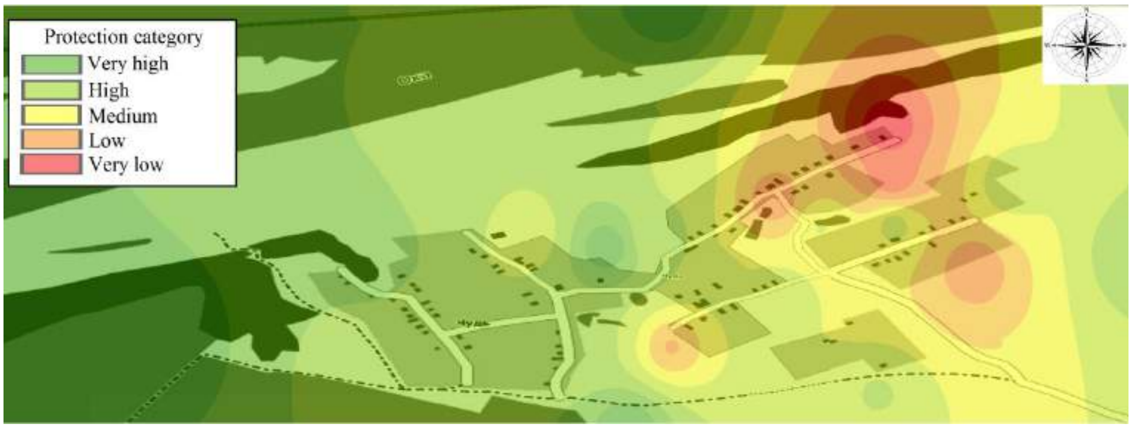

Figure 7. Results of the the vulnerability assessment of karst waters in the territory of the Chud village

The study area was divided into the area of protective soil over-karst cover, the area of underground runoff and the area of karst water discharge, atmospheric precipitation infiltration and karst water mineralization. The separation of zones of karst waters vulnerability in the territory of the Chud village was performed using the method of inversely weighted distances (IDW). The discrepancy between the karst waters vulnerability obtained during regime observations using the hydrogeological control system and the assessment of the vulnerability of karst groundwater based on the indicators of the geological structure and protective properties of the soil cover, the concentration of runoff, precipitation regime and mineralization of karst waters is no more than 15%.

4. CONCLUSIONS

In this work, mapping of the vulnerable territory of the Chud village was carried out, using the assessment methodology for the protection of karst groundwater. Based on the factors {O,C,K,P,L}, an expert assessment of the vulnerability of sources of non-centralized water supply was formed. The division into the area of protective soil over-karst cover, the area of underground runoff and the area of karst water discharge, atmospheric precipitation infiltration and karst water mineralization is carried out. The separation of zones of karst waters vulnerability in the territory of the Chud village was performed using the method of inversely weighted distances (IDW). The vulnerability assessment of karst waters was carried out in the area of 10 key control points identified during the deployment of the hydrogeological control system in 2017.

The discrepancy between the assessment of the vulnerability of karst waters obtained during regime observations using the hydrogeological control system and the assessment of the vulnerability of karst groundwater based on the indicators of the geological structure and protective properties of the soil cover, the concentration of runoff, precipitation regime and mineralization of karst waters is no more than 15%. This can be explained by the fact that direct measurements are more preferable in the case of accurate determination of key points of hydrogeological monitoring. However, in this case, covered karst prevails on the territory of the Chud village and here the water flows down towards craters, basins, karst ditches, where it is absorbed by cracks. As a result, it is necessary to take into account the peculiarities of the movement of meltwater and precipitation along vertical cracks, since according to regime observations, near-surface zones with increased fracturing are widely represented in this territory. Nevertheless, the approach presented in this paper avoids costly monitoring methods and reduces the use of direct measurements.

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