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Vulnerability Assessment of Karst Underground Waters in the Territory of Non-Centralized Water Supply

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Abstract. This paper considers an individual approach to assessing the vulnerability of karst groundwater. It is based on the allocation of such indicators as the geological structure of the observed territory, the concentration of runoff entering the karst channels, and the precipitation regime. Due to regional climatic, hydrogeological and landscape features, a private methodology for assessing the vulnerability of karst groundwater has been developed. To assess the vulnerability of sources of non-centralized water supply, a factor is taken into account, including such indicators as lithology, soil thickness, and the presence of a karst base. The most intense karst processes occur on river terraces, valley slopes. For this purpose, a factor is taken into account, including the level of river flow by hydrogeological posts, underground flow, karst craters, tectonic faults, and vegetation. The development of karst is also promoted by high gradients of the underground flow and underground water outlets in riverbeds and coastal slopes. For this purpose, the factor is taken into account, which is formed on the basis of the criterion of the development of the karst network and the hydrographic network.
A relatively large amount of precipitation, especially in the form of rain, and low evaporation determine the increased values of surface and underground runoff and, accordingly, the development of dissolution and leaching processes. Among the external factors, the solubility of minerals is significantly affected by the total mineralization and chemical composition of the dissolving waters. As a result of the observations, spatio-temporal dependencies were identified in the controlled territory.

1. Introduction
Karst groundwater is often the only freshwater resource for many regions and cities around the world. Reliable provision of the population of such territories with high-quality water supply is an urgent task, especially in the presence of active karst processes [1]. Karst water exchange systems have a high natural and anthropogenic vulnerability of groundwater and a low ability to self-purify from pollutants [2,3]. One of these regions is the Nizhny Novgorod region (the territory of the Oka karst) [4].

Maintaining the high quality of underground karst water in areas with non-centralized water supply requires the use of special scientific and methodological approaches based on knowledge of the specifics of the hydrogeology of the karst and local natural and anthropogenic conditions [5]. One of the generally accepted approaches to justifying the zoning and protection regime of groundwater resources is to assess their vulnerability to pollution [6]. There are many different methods and approaches for assessing the vulnerability of groundwater [7-11], which are based on methods of hydrogeological zoning, indexrating and parametric methods, etc. Methods of mapping vulnerable territories where water supply to the population is provided by wells are used. A geographic information system (GIS) is used, which simplifies the construction of a vulnerability map. Using the analysis of a digital topographic model, GIS allows you to automatically determine the classes of infiltration conditions. To assess the vulnerability of sources of non-centralized water supply, it is possible to distinguish such indicators as the geological structure and protective properties of the soil cover, the concentration of flow entering karst channels, the precipitation regime and the mineralization of karst waters.

Thus, the purpose of this work is to develop a methodology for assessing the vulnerability of karst groundwater in the territory of non-centralized water supply, based on the indicators of the geological structure and protective properties of the soil cover, the concentration of flow, the development of the karst network, the precipitation regime and mineralization of karst waters.

2. Methodology of multi-criteria assessment of non-centralized water supply

Due to regional climatic, hydrogeological and landscape features, it is advisable to develop multi-criteria methods for the qualitative assessment of karst groundwater for the needs of non-centralized water use [12,13]. This technique can be built on the basis of an interval estimate, which allows using sample data to find a two-sided interval in which, with a given probability, lies the true but unknown value of the rank of the distribution parameter. Confidence probability is set a priori 95% based on regulatory requirements [14].

The boundaries of the confidence interval are:

$$\bar{x} - g\frac{\sigma}{\sqrt{n}} \le \mu \le \bar{x} + g\frac{\sigma}{\sqrt{n}} \quad (1)$$

where μ – mathematical expectation of the factor rating;

$\bar{x}$ – the sample average that contains μ;

σ – the average square deviation from the average;

g – tabulated significance level (found in the Laplace function table)

n – the number of values in the selection.

A generalized multi-criteria assessment based on rank estimates θ, is made on the basis of an integral indicator:

$$\Theta = \sum_{i=1}^{n} \Omega_r w_i \quad (2)$$

where Ω_r – rank estimates of the indicators of the geological structure and protective properties of the soil cover, the concentration of runoff, the development of the karst network, the precipitation regime and mineralization of karst waters;

$w_1, w_2, \ldots, w_n$ – weight coefficients.

3. Criteria for assessing the state of ground water of non-centralized water supply

To assess the vulnerability of non-centralized water supply sources on the territory of the Nizhny Novgorod region, a factor O is taken into account, including such indicators as lithology, soil capacity, thickness of the overkarst base. $O = \{O_L, O_M, O_K\}$:

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Table 1. Rating by lithology, soil capacity, thickness of the overkarst base.

Lithology O_L	Rating	Soil capacity O_M, м	Clay, rating	Sandy, rating	Thickness of the overkarst base O_K, м	Rating
Clays	9	>1,2	9	6	>10	6
Loam	8	0,3-0,7	6	3	5-10	3
Marls	6	0,1-0,3	3	1	<5	0
Sandstones, gravel	3	≤0,1	1	0		
Karst rocks	1					
Open karst sinkholes	0					

$O_r = O_L + O_M + O_K$

Table 2. Vulnerability classes.

O_r	Protection category
0-2	Very low
2,5-4	Low
4,5-6	Medium
6,5-8,5	High
9-21	Very high

The most intensive karst processes occur on river terraces, the slopes of the valleys of the rivers Oka, Tesha, Serezha, Bol. Kutra. Factor C includes the level of river flow at hydrogeological stations, groundwater flow, sinkholes and vegetation. $C = \{C_Q, C_D, C_K\}$:

Table 3. Rating by the level of river flow, the number and depth of sinkholes, vegetation.

Average annual river flow C_Q m^3/s	Rating	Number of sinkholes km^2 C_d	Depth of a sinkhole, m	Rating	Vegetation cover, C_K		
>1000	9	>40	>20	9	Slope %	Density	Rare
100-1000	7	20-40	10-20	7	<8	9	8
25-100	5	5-20	5-10	5	8-31	8	7
5-25	2	0-5	<5	2	>31	7	5
<5	0						

$C_r = C_Q + C_D + C_K$

Table 4. Vulnerability classes.

C_r	Protection category
0-2	Very low
2,5-4	Low
4,5-6	Medium
6,5-8,5	High
9-27	Very high

The development of karst is also facilitated by high gradients of underground flow and groundwater outflows in river beds and coastal slopes [15]. For this, factor K is taken into account, which is formed on the basis of the criterion of the development of the karst network and the hydrographic network. $K = \{K_R, K_t, K_P\}$:

Table 5. Rating of the development of the hydrographic network.

Density of the hydrographic network K_R km / km^2	Rating	Permeability K_p	Rating	Time to reach the outlet (day))K_t	Rating
>0,4	1	Fractured	6	>10	6
0,3-0,4	3	Transitional	3	1-10	3
0,2-0,3	6	Channel	1	≤1	1
0,1-0,2	7				
0-0,1	9				

$K_r = K_R + K_t + K_p$

Table 6. Vulnerability classes.

K_r	Protection category
0-2	Very low
2,5-4	Low
4,5-6	Medium
6,5-8,5	High
9-21	Very high

A relatively large amount of precipitation, especially in the form of rain, and low evaporation determine the increased values of surface and underground flow, 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 [16]. The P factor takes into account the amount of liquid and solid sediments involved in the feeding of karst waters.

Table 7. Rating of the amount of liquid and solid precipitation.

Average precipitation P, mm	P_r	Protection category
>600	6	Very low
500-600	4	Low
400-500	2	Medium
<400	1	High

Among external factors, the solubility of minerals is significantly affected by the total mineralization and the chemical composition of the dissolving waters [4]. The L factor characterizes the electrical conductivity, mineralization and temperature of karst groundwater. $L = \{L_M, L_L\}$:

Table 8. Rating on mineralization and electrical conductivity of karst waters.

Mineralization L_M mg/l	Electrical conductivity L_L mSm/cm	L_r	Protection category
>1,2	>1,2	9	Very low
0.6-1,2	0,8-1	6	Low
0,3-0,5	0,4-0,7	3	Medium
<0,3	<0,4	1	High

4. Experimental data

In 2017, on the territory of the village of Chud in the Navashinsky district of the Nizhny Novgorod Region, studies were conducted using the developed hydrogeological control system based on the identification of key zones of geodynamic karstological monitoring and the use of local hydrogeological control based on geoelectric methods [4,17].

In 2021, mapping of the vulnerable territory of the village of Chud was carried out, using the methodology for assessing the protection of karst groundwater. The vulnerability of karst waters was assessed at 10 key control points identified during the deployment of the hydrogeological control system in 2017, based on the developed methodology [18]. Highlighted: zones of safe drinking water use (green), zones of limited water use with a temporary restriction during the periods of 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 1'.

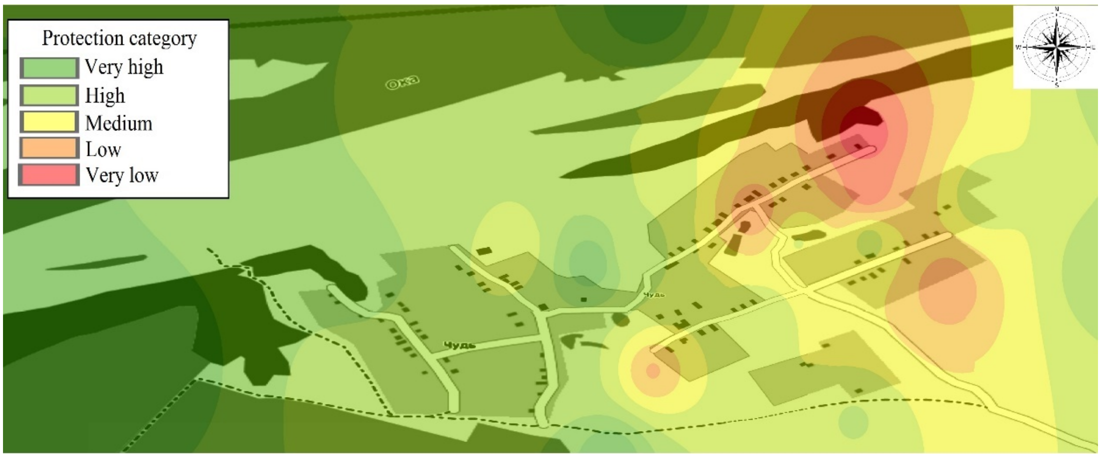

Figure 1. The results of the assessment of the vulnerability of karst waters in the territory of the village of Chud.

The study area was divided into areas of protective soil over karst cover, areas of underground flow and the area of karst water discharge, atmospheric precipitation infiltration and karst water mineralization. The division of zones of vulnerability of karst waters in the territory of the village of Chud was carried out using the method of inversely distances weighted (IDW) [19,20].

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 flow, precipitation regime and mineralization of karst waters is no more than 15%.

5. Conclusion

In this work, mapping of the vulnerable territory of the village of Chud was carried out, using the methodology for assessing 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 of zones of vulnerability of karst waters in the territory of the village of Chud was carried out using the method of inversely distances weighted (IDW). The vulnerability of karst waters was assessed at 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 flow, precipitation regime and mineralization of karst waters is no more than 15%.

On the territory of the village of Chud, covered karst prevails and here the water flows towards craters, hollows, karst ditches, where it is absorbed by cracks and ponors. When using wells for drinking water supply, it is necessary to take into account the movement of melt water and sediments along

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vertical cracks, since according to the data of regime observations, near-surface zones with increased fracturing are widely represented in this territory.

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