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Assessment of Karst Groundwater Vulnerability to Contamination as a Tool for Delineation of Source Protection Zones: A Case Study in the Crimean Mountains

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Abstract: The assessment of groundwater vulnerability to contamination provides a hydrogeological basis for the designation of protection zones for drinking water sources. This paper presents a case study from the Crimean Mountains where karst groundwater plays a primary role in water supply. Groundwater vulnerability assessment has been carried out for two large karst springs: the Ayan and Krasnopeshcherny. For this purpose, a method adapted to the conditions of karst water formation in the region, called the Mountain-Crimean method, was used. The resulting source vulnerability maps of selected test sites demonstrate both similarities and differences. The common feature is the area predominance of the moderate vulnerability class, with a minor share of the low vulnerability class. However, the vulnerability classes on the two catchments have different placement patterns, as does the presence or absence of a high vulnerability class. The catchment area of the Krasnopeshcherny spring appeared to be more sensitive to pollution than the Ayan spring. The main reason is the hydrodynamic conditions of the deep parts of the karst aquifers drained by the springs. The karst aquifer of the Krasnopeshcherny spring has a much higher groundwater flow dynamic than that of the Ayan spring. The study closes by proposing a scheme of transition from vulnerability map to sanitary protection zones for karst water intakes in accordance with the regulatory standards of the Russian Federation.

Keywords: karst aquifer, groundwater, vulnerability to contamination, Crimean Mountains, sanitary protection zone, assessment, regional method, water supply source, phreatic zone.

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1. Introduction

Karst aquifers are widely distributed across the Earth's land mass. As reported in [*Stevanović*, 2019], karstified rocks crop out over > 14% of ice-free land. In Russia, more than 60% of the territory is underlain by soluble rocks [*Kotlyakov*, 2007]. Karst groundwater serves as a crucial source of drinking water in many parts of the world due to its high natural quality and abundance. Although it accounts for only about 9.2% of global water consumption [*Stevanović*, 2019], it holds significant importance in several countries and regions, including the Balkans, Central and Western Europe, the Middle East, parts of North America's southern regions, North Africa, and the Western Caucasus.

The Crimean Peninsula, where soluble rocks occupy over 84% of its area [*Dublyansky and Dublyanskaya*, 1996], also belongs to such karst water dependent regions. Karst aquifers account for almost all fresh groundwater resources (> 90%) of the peninsula [*Vakhrushev et al.*, 2022]. In Crimea, about 100 karst springs have an average discharge rate exceeding 0.01 m^3/s [*Dublyansky and Dublyanskaya*, 1996]. Of these, about 20 springs have an average discharge rate greater than 0.1 m^3/s and 2 springs (Karasu-Bashi and Skelsky) – greater than 1 m^3/s. Karst springs play a leading role in formation of river flow of the peninsula

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and filling of drinking water reservoirs. Under the conditions of the ongoing rapid socio-economic development of the Crimean region and the continuing water shortage, the issue of preserving the quality and quantity of karst water resources is particularly important.

Karst aquifers, unlike pore and fracture aquifers are characterized by extremely high heterogeneity and anisotropy of capacitance and filtration properties. Most groundwater flow occurs primarily through conduit systems. Accordingly, karst aquifers exhibit peculiar hydrogeological features, among which are high flow concentration, focal nature of recharge and discharge, and high groundwater flow velocities [*Ford and Williams*, 2007; *Klimchouk*, 2008]. As a result, karst waters have a very high overall susceptibility to contamination and a low capacity for self-purification.

Assessing groundwater vulnerability to contamination is a key step in designing effective protection measures for drinking water sources [*Farics et al.*, 2021; *Ravbar et al.*, 2021]. Due to their specific hydrogeological features, assessment of groundwater vulnerability in karst aquifers requires special approaches. Such approaches and methods have been developed primarily in European countries over recent decades [*European Commission: Directorate-General for Research and Innovation*, 2004; *Iván and Mádl-Szőnyi*, 2017; *Ravbar*, 2007].

For the conditions of the Crimean Mountains, a regional modification of the karst groundwater vulnerability assessment methodology has been developed. Previously it was tested on four karst massifs including the Chatyrdag, Dolgorukovsky, Karabi, and Ay-Petri. As a result, maps depicting the vulnerability of groundwater resources to contamination were created [*Tokarev et al.*, 2024].

This study aims to assess the vulnerability of groundwater sources to contamination at the largest karst water outlets on the Chatyrdag and Dolgorukovsky massifs – the Ayan and Krasnopeshcherny springs, which supply water to the city of Simferopol. To achieve this, a regional adaptation of the groundwater vulnerability assessment methodology was applied. The results provide a foundation for designating sanitary protection zones around these sources.

2. Description of the Study Areas

The Ayan (average discharge rate 0.6 m^3/s) and Krasnopeshcherny (0.15 m^3/s) karst springs are located in the central part of the Main Range of the Crimean Mountains (Figure 1a, b). The springs discharge large karst aquifers (KAs). They give rise to the largest tributaries of the Salgir river in the upper part of its basin (average flow rate 1.3 m^3/s). Both springs have highly variable discharge rate dynamic and show rapid response to precipitation events in the recharge area. During continuous low water periods, discharge rate of the springs is reduced to 0.005 m^3/s. On heavy floods, spring discharge may increase rapidly up to 20 m^3/s.

2.1. Ayan Karst Spring, Chatyrdag Massif

2.1.1. Physiography of the Chatyrdag Massif

The Ayan karst spring (44°49’35.6”N, 34°17’30.2”E, altitude 450 m a.s.l.) is located at the northern foothill of the Chatyrdag massif. The area of the massif is about 47 km^2. Approximately half of it represents drainless catchments on the plateau surface and the other half corresponds to the open catchments on the slope of the massif. Two distinct levels are evident on the surface of the Chatyrdag: the Lower Plateau in the north (900–1150 m a.s.l.) and the Upper Plateau in the south (1300–1500 m a.s.l.), with their areas in a ratio of 5:1.

Various surface karst forms are widespread on the Chatyrdag massif, particularly on the plateau, including karst dolines, blind gullies, and karren fields. The total number of dolines exceeds 500. Depths of dolines in most cases (ca. 90%) do not exceed 10 m. The average density of dolines on the Chatyrdag plateau is 22 dolines/km^2. In central part of the lower plateau it reaches 60 dolines/km^2. Such a wide distribution of dolines on the

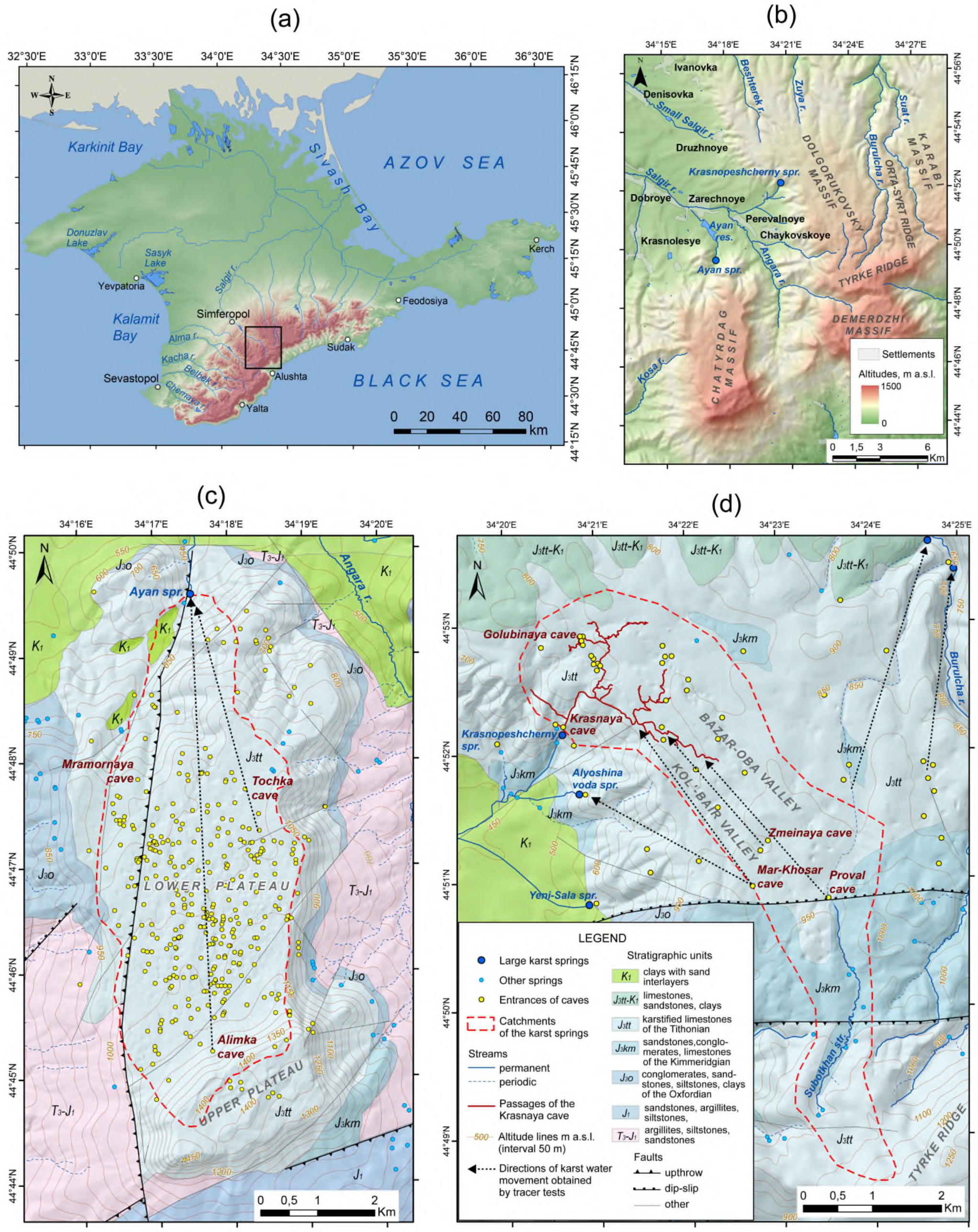

Figure 1. Position of the study area (rectangle) on the map of the Crimean Peninsula (a); physiographic map of the study area (b); and the maps of geological and hydrogeological settings of the Chatyrdag (c) and Dolgorukovsky (d) karst massifs. Geological information (stratigraphic units and faults) is derived from [*State geological survey*, 2008].

plateau indicates, on the one hand, the development of epikarst and, on the other hand, a significant share of focal infiltration of precipitation in recharge of karst waters.

The plateau is dominated by steppe and shrub vegetation with patches of forest restricted to dolines. The slopes of the massif are covered with forests and sparse woodlands. On the plateau and slopes of the massif, low (0–20 cm) and medium-thickness (20–40 cm) soils predominate. In bottoms of dolines soil thickness can reach 80–100 cm. Soils are clayey and loamy with a high proportion of rubble.

2.1.2. Geology and Hydrogeology of the Chatyrdag Massif

The Chatyrdag massif is hydrogeologically isolated from adjacent massifs of the Main range of the Crimean Mountains. It comprises two distinct rock sequences (Figure 2a) with significantly different hydrogeological properties. The lower sequence consists of low-permeability Upper Triassic and Lower Jurassic flysch sediments, including mudstones, siltstones, and sandstones. This sequence acts as an aquitard and is practically devoid of groundwater, except for narrow zones of tectonic fracturing. The upper sequence is composed of Upper Jurassic limestones which are characterised by intense tectonic dislocation, fracturing and karstification. It contains the aquifers with highly developed karst conduit permeability. The KA drained by the Ayan spring is the largest on the massif.

There are two main models of the tectonic structure of the Chatyrdag massif. Most karstologists and hydrogeologists use the fold-block model and consider the Chatyrdag as an autochthonous massif [*Dublyansky and Kiknadze*, 1984]. Some geologists argue for the thrust (overthrust) model of the Chatyrdag tectonic structure [*Kazantsev et al.*, 1989; *Yudin*, 2011]. According to V. V. Yudin, Chatyrdag is an allochthonous massif – olistolite (olistoplaque) – that was thrust onto the underlying terrigenous strata during the Early Cretaceous.

The karst waters are recharged exclusively by atmospheric precipitation. The average annual precipitation in the central part of the Crimean Mountains is 700–900 mm and the evapotranspiration is about 400 mm [*Vyed'*, 2000]. Thus, the annual effective precipitation recharging karst groundwater is 300–500 mm. Quantitatively, precipitation of the cold part of the year (November-March) prevails. Considering the relatively low rates of evapotranspiration during this period, karst waters recharge is provided mainly by winter precipitation. This is confirmed by the isotopic composition of waters of large karst springs, which is significantly shifted to the winter precipitation signal and practically does not change during the year [*Dublyansky et al.*, 2019].

To date, 355 karst caves are known on the Chatyrdag massif, most of them are vertical shafts [*Russian Geographical Society*, 2024]. The deepest shafts reach a depth of 250 m. However, none of the shafts reach the phreatic (saturated) zone of the massif. The density of caves is maximal in central part of the plateau reaching 40 caves/km².

Stratigraphic units (see Legend in Figure 1d): 1 – J_3tt; 2 – J_3km; 3 – J_3o; 4 – T_3-J_1; 5 – K_1. 6 – tectonic faults; 7 – karst caves, 8 – large karst springs, 9 – small springs, 10 – karst water table. Descending flow in vadose zone: 11 – through fractures and small conduits (slow component); 12 – through large conduits (fast component). Lateral flow in phreatic zone: 13 – slow circulation; 14 – fast circulation. 15 – Quaternary calcareous tuffs.

2.1.3. Characteristics of the Ayan Spring

The Ayan spring is associated with a regional tectonic fault bounding the massif from the north-west (Figure 1c). The spring represents a single rising outlet of karst water, equipped with a spring collection system in 1928. The karst water outlet is directly connected with the cave passages explored for a total length of 500 m and mostly located below the karst water table.

In hydrogeological investigations on karst massifs, a key problem is the delineation of KASs catchments, since their boundaries generally do not correspond to topographic watersheds. To solve this problem, the data of structural-geological survey, speleological works, water-balance calculations are involved. Especially valuable information is provided by the results of tracer tests. Using a combination of the above methods, the catchment area of the Ayan karst spring was identified to be approximately 23 km^2. It includes the entire lower plateau and the northern part of the upper plateau of the Chatyrdag massif (Figure 1c).

Tracer tests, besides clarifying the structure of underground catchments, provide information on the direction and velocity of karst water movement. In addition, the density and duration of the tracer output indicates the degree of dilution and attenuation of the possible contaminant. Based on the results of tracing experiments, the average karst water

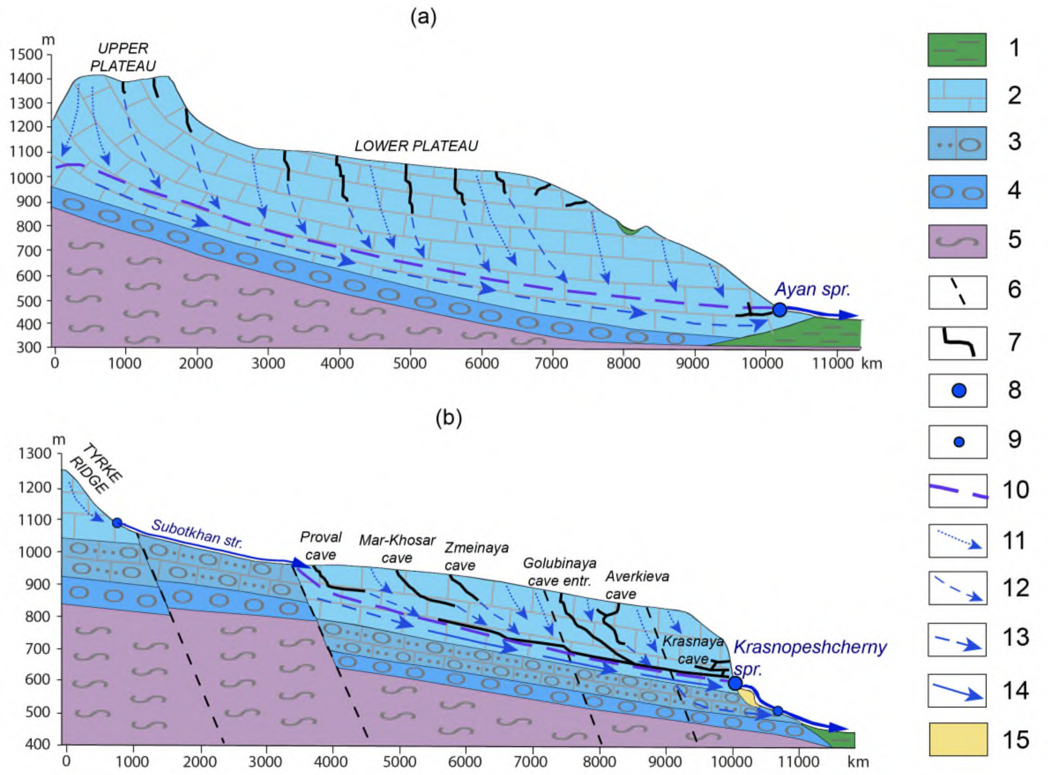

Figure 2. Simplified geological and hydrogeological cross-sections of the Chatyrdag (a) and Dolgorukovsky (b) massifs depicting the catchment areas of the Ayan and Krasnopeshcherny karst springs.

velocity of the Ayan KA in high-water period is 1150 m/day. The concentration of tracers at the spring was very low, indicating a strong dilution along the way of karst water movement. It most likely occurs in the phreatic zone of the massif, which appears to have a high storage capacity and relatively low hydraulic conductivity that retard tracer transit.

2.2. Krasnopeshcherny Spring, Dolgorukovsky Massif

2.2.1. Physiography, Geology and Hydrogeology of the Dolgorukovsky Massif

The Krasnopeshcherny spring (44°52’12.5”N, 34°20’35”E, altitude 570 m a.s.l.) represents a group of compactly located karst water outlets on the western slope of the Dolgorukovsky massif (Figure 1b).

The area of the Dolgorukovsky massif, excluding the Tyrke ridge, is about 52 km^2. The massif has a vast plateau surface called Yayla. Four dry karst-erosion valleys intersect the Yayla from south to north. There are numerous karst dolines at their bottoms. The total number of the dolines is about 130. Their density is relatively low, rarely exceeding 20 dolines/km^2. On the Yayla, soil cover consists of low- to medium-thickness varieties under steppe vegetation, and thicker varieties under meadow and forest vegetation.

Karst waters are recharged mainly by diffuse infiltration, but concentrated infiltration (influation) also common. There is a permanent stream Subotkhan in the southern part of the plateau. It is typically completely swallowed up by sinkholes near the Proval cave, though a significant portion reaches the Burulcha river basin during heavy floods. Also, temporary streams may periodically appear on dry valleys slopes, which are swallowed up by sinkholes in their bottoms. In summer, a significant portion of karst water recharge can be provided by condensation [*Dublyansky and Kiknadze*, 1984].

Several KAs are known within the Dolgorukovsky massif. Some of them discharge on the eastern slope of the massif, feeding the Burulcha river and its tributaries, others discharge on the western slope in the Salgir river basin. Some part of the groundwater of the Dolgorukovsky massif is not discharged on the slopes, but flows to the north and feeds artesian basins of the Crimean Piedmont.

The geological structure and hydrogeological conditions of the Dolgorukovsky massif differ significantly from the Chatyrdag massif. The main karst aquifers of the Dolgorukovsky massif are hosted by Titonian limestones. They are underlain by thick layer of Kimmeridgian conglomerates and sandstones (Figure 2b). It acts as an aquitard for KAs discharging on the western slope of the massif [*Dublyansky et al.*, 2002].

2.2.2. Characteristics of the Krasnopeshcherny Spring

The Krasnopeshcherny spring discharges the KA of the Krasnaya Cave (also known as Kizil-Koba) – the largest cave in the Crimea with the total length exceeding 20 km. The lower levels of the cave are in the phreatic zone. According to results of our dye tracing tests, in high-water periods karst water velocity in the Krasnaya cave system can reach 8 km/day.

Transit of karst water to the discharge points is carried out by well-developed conduit systems, most of which have been investigated and surveyed by speleologists. The Golubinaya cave, which has an entrance on the plateau, was traversed to the junction with the Krasnaya cave. Tracer experiments proved the connection of the Krasnaya cave KA with other large caves on the plateau, e.g., Mar-Khosar (1300 m long), Proval (1250 m), Zmeinaya (850 m) (Figure 1d).

The combined results of speleological exploration and tracer tests allowed delineation of the catchment area of the Krasnaya cave KA with an area of about 15 km^2. The catchment is divided into inner and outer parts. Its inner part comprises the Kol'-Bair and Bazar-Oba dry valleys located in the central and western parts of the Yayla with altitudes 750–950 m a.s.l. The vegetation cover here is mainly steppes on watersheds and slopes and meadows in valley and bottoms of dolines. That area provides an autogenic recharge of the KA, characterised by a rapid signal path from the precipitation events to the Krasnopecherny spring. The outer part corresponds to the Subotkhan stream valley with an area of about 2 km^2 and altitudes 950–1200 m a.s.l., which provides allogenic recharge of the KA. The vegetation of that area is mainly broadleaved forests with patchy meadows.

3. Methodology

The term "vulnerability of groundwater" refers to the susceptibility of a hydrogeological system to contamination, as well as its capacity to neutralize or mitigate such contamination [*Ravbar*, 2007]. To date, many methods have been developed for assessment of karst groundwater vulnerability to contamination (KGV), considering their unique hydrogeological characteristics [*European Commission: Directorate-General for Research and Innovation*, 2004; *Iván and Mádl-Szőnyi*, 2017; *Ravbar*, 2007]. They differ in the estimation procedures, the factors considered, and the resulting outputs.

There is a general methodology that outlines the basic assessment framework and groups of factors to be considered, called the European approach [*Daly et al.*, 2002]. It is based on the "hazard-pathway-target" conceptual model. "Hazard" refers to a potential source of contamination, typically located on the ground surface. "Target" refers to a groundwater object that may be contaminated by a "hazard". The target may be the entire groundwater body or individual groundwater outlet, such as spring, well, or borehole. In the first case the subject of assessment is referred to as "resource vulnerability", while in the second case it is called "source vulnerability". "Pathway" refers to a flow route from the "hazard" to the "target". In the case of resource vulnerability it represents a downward flow through vadose zone of aquifer. If the object of assessment is a specific groundwater outlet (i.e., "source vulnerability"), the pathway of potential pollutant through the phreatic zone of aquifer must also be considered.

The European approach to KGV assessment proposes four groups of factors to be considered: overlying layers above groundwater body (factor O), flow concentration (factor C), precipitation regime (factor P), and development of karst network in phreatic zone (factor K). Factor O characterizes the protective function of the aquifer against contaminant provided by the geological layers in the vadose zone. Factors P and C assess the reduction in this protective function due to heavy rainfall and bypassing of the protective layers by water flows, which can lead to rapid introduction of contaminants into the groundwater. Factor K evaluates the conditions that affect the passage of contaminants through the phreatic zone to groundwater intakes. Thus, the factors O, C and P are used for assessment of resource vulnerability. In the case of source vulnerability assessment, all of four factors have to be evaluated, including factor K.

To date, numerous methods of KGV assessment have been developed; most of them are index methods based on the European approach. Some of them are intended only for resource vulnerability assessment. The most popular ones are the PI method [*Goldscheider et al.*, 2000], COP method [*Vías et al.*, 2006], DRISTPI method [*Jiménez-Madrid et al.*, 2013], and IKAV method [*Moreno-Gómez et al.*, 2022]. A relatively broad variety of methods provide the ability to assess a source vulnerability of karst waters. Among them are the EPIK method [*Doerfliger et al.*, 1999], Slovene approach [*Ravbar and Goldscheider*, 2007], COP+K method [*Andreo et al.*, 2008], PaPRIKa method [*Kavouri et al.*, 2011], and KAVA method [*Biondić et al.*, 2021]. Many of them have been widely tested in different regions of the world, demonstrating their high effectiveness. There are many examples of recent studies using these methods [*Marín et al.*, 2021; *Petrović*, 2020; *Steiakakis et al.*, 2023; *Yogafanny and Legono*, 2021].

It should be noted that in many cases, a comparison of the KGV maps for the same test area derived using different assessment methods revealed significant differences between them [*Marín et al.*, 2011; *Moreno-Gómez et al.*, 2019; *Polemio et al.*, 2009; *Ravbar and Goldscheider*, 2008]. This is manifested even when methods with the same methodological basis, similar input information and estimation procedure are used [*Farics et al.*, 2021; *Marín et al.*, 2014]. It can be concluded that there are no universal methods for KGV assessment. Thus, a careful selection or adaptation of existing methods to regional conditions is necessary to achieve the most adequate assessment results.

The conditions of karst water formation in the Mountain Crimea have their own peculiarities, including a significant share of winter precipitation (snow) in their recharge, predominance of infiltration processes due to the almost complete absence of impermeable cover on the karst massifs, well-developed epikarst zone acting as a protective layer retaining the groundwater contaminant. To account for these features, a regional KGV assessment method designated as the Mountain-Crimean method was developed [*Tokarev et al.*, 2024], based on COP and Slovene methods. The basis for its construction is the methods COP and Slovene. The adjustments included the consideration of epikarst's protective function, the addition of factors characterizing the concentration of underground flow in the vadose zone, and the substitution of mapping individual karst landforms with the use of the spatial density. The Mountain-Crimean method was originally designed for resource vulnerability assessment, but can be extended to assess source vulnerability by adding an additional group of factors. Specifically, for this purpose, the factor K block from the Slovene approach was added to the assessment scheme (Figure 3)

The mapping, calculations, construction of intermediate layers and final vulnerability maps were carried out using ArcGIS 10 software. Initial information on hydrogeological, geomorphological and landscape-topographic conditions was obtained from literature and archive sources. Input analogue data was digitised and converted into geodata formats to perform the assessment procedure in a GIS environment. To estimate the K factor, both archival materials and the results of recent tracer tests were used.

4. Results and discussion

4.1. Assessment of Karst Groundwater Source Vulnerability to Contamination

The resulting maps of karst groundwater source vulnerability for catchment areas of the two selected springs, as well as the maps of the individual factors, are shown in Figure 4 and Figure 5. As observed, the spatial distribution of vulnerability classes

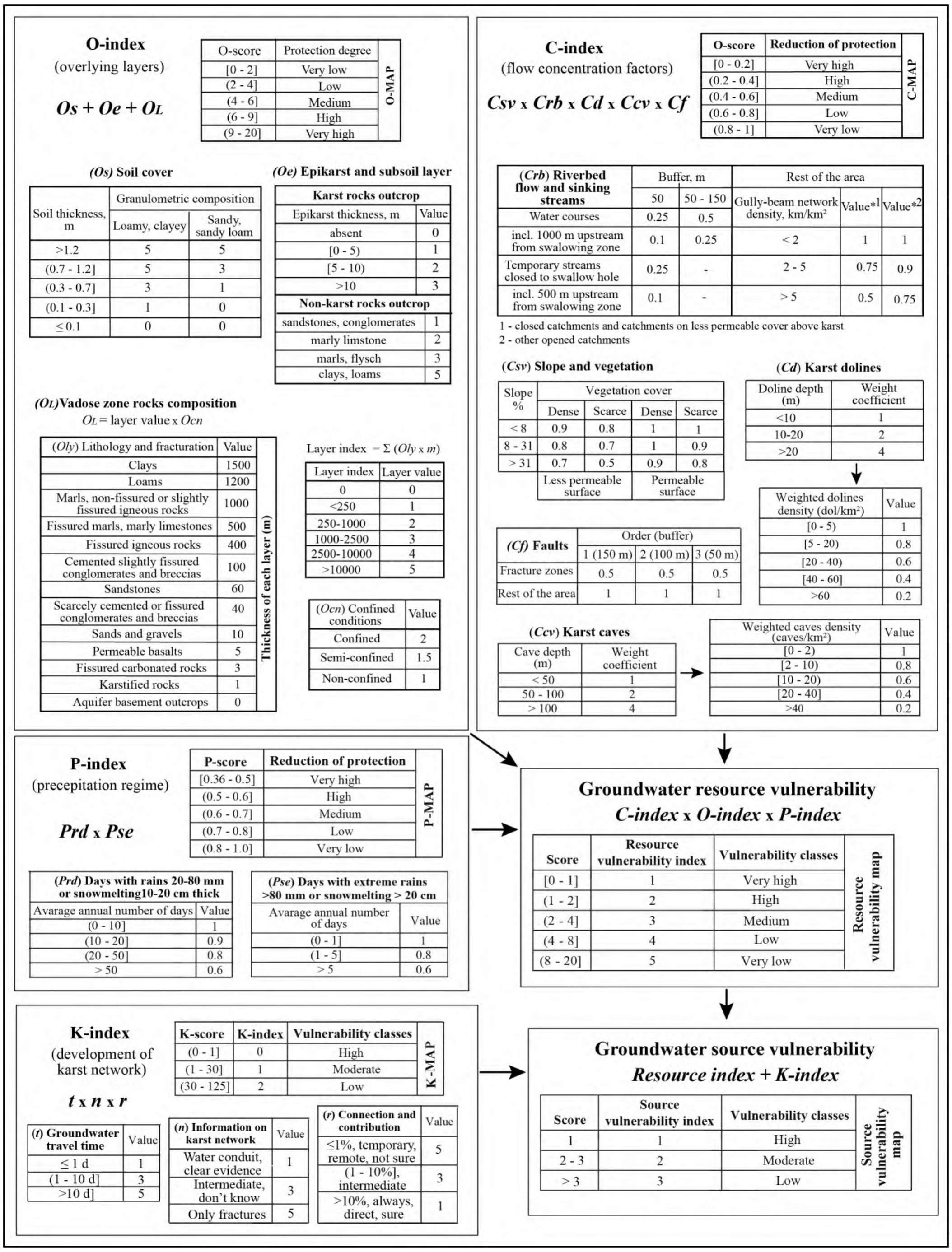

Figure 3. The scheme of the Mountain-Crimean method adapted to groundwater source vulnerability assessment. The block of K-index is taken from the Slovene approach [*Ravbar and Goldscheider*, 2007].

at the two test sites shows both similarities and differences. A common feature is the predominance of the moderate vulnerability class, with a small proportion of the low vulnerability class. However, the placement patterns of the vulnerability classes differ between the two catchments, as does the presence or absence of a high vulnerability class.

Within the catchment area of the Ayan spring, the low vulnerability class occupies about 36% of the area, while the moderate class occupies about 64% of the area. The moderate vulnerability class includes almost the entire the Lower plateau of the Chatyrdag massif and the surroundings of the Ayan spring. The majority of the northern slope of the massif, as well as the slope between the Upper and Lower plateaus, has been assigned a low vulnerability grade. Exceptions to this are gullies enclosed by karst sinkholes and tectonic

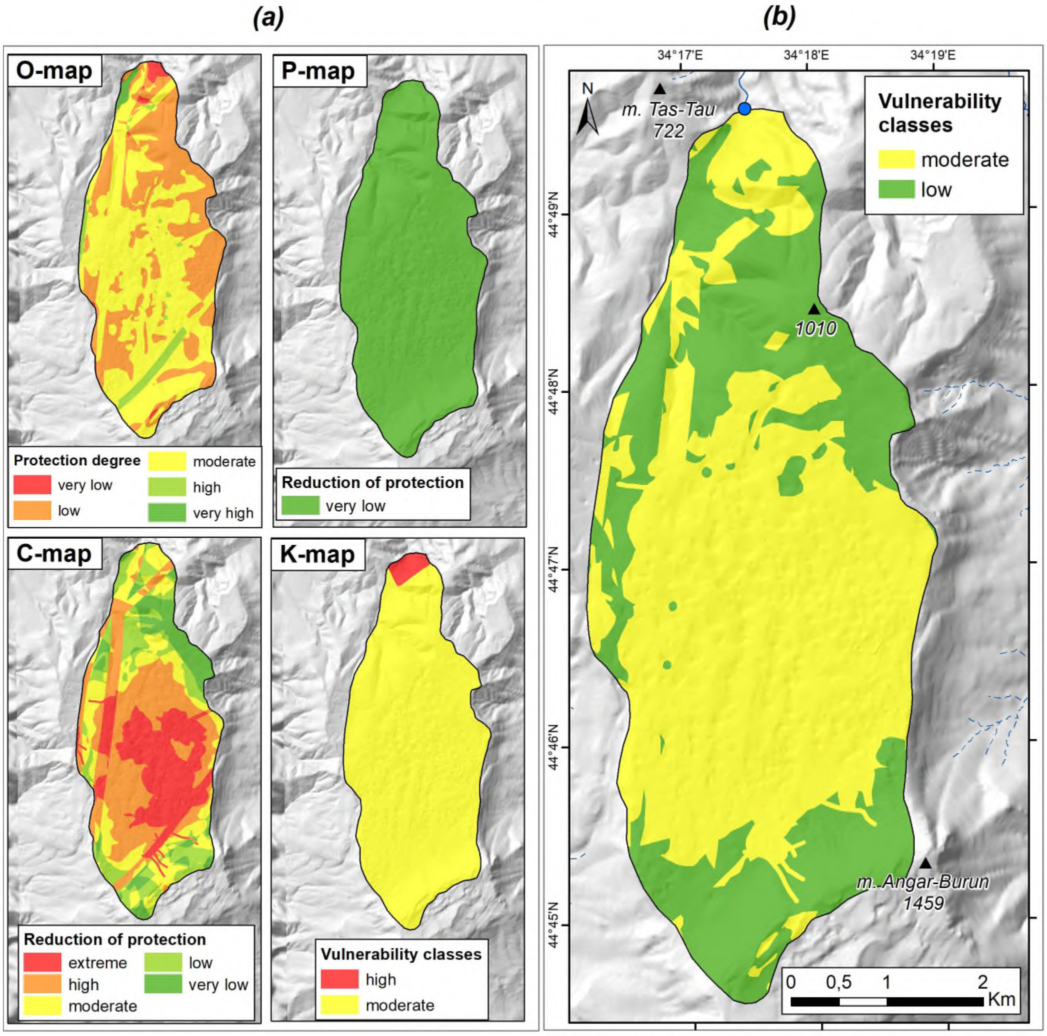

Figure 4. The maps of vulnerability factors (a) and the vulnerability map (b) of the Ayan karst spring.

fracture zones, which have a moderate vulnerability class. On the Upper plateau, areas occupied by karst valleys and dolines also have moderate vulnerability. Notably, the high vulnerability class is completely absent in this catchment.

The assessment results within the Krasnopeshcherny spring catchment revealed a significantly different situation. Approximately 38% of the assessed area was classified as having low vulnerability to contamination. This class is primarily concentrated in the southern part of the catchment, along the slopes of the Subotkhan stream valley, and on the eastern periphery of the basin. The separate areas of low vulnerability are also located as on the western slope of the massif in the vicinity of the Krasnopeshcherny spring. The moderate vulnerability class covers about 58% of the catchment area. It mainly occupies karst-erosion valleys on the plateau, the western slope of the massif and the bottom of the Subotkhan valley with its tributaries in the upper and lower reaches. Just over 4% of the catchment was classified as having high vulnerability class. The most vulnerable areas are the bottoms of gullies with periodic and permanent watercourses, including the part of Subotkhan valley before the sinking zone, and the areas of high density of karst dolines and caves in the northwestern part of the plateau.

Obviously, the absence of high source vulnerability class in the Ayan catchment is due to the hydrodynamic conditions of the deep part of the KA lying in the phreatic zone of the Chatyrdag massif. The relatively low velocity of underground flow in the Ayan KA prevents a potential pollutant from rapidly reaching the spring outlet. In contrast, the Krasnopeshcherny KAS exhibits high groundwater flow dynamics, resulting in the rapid

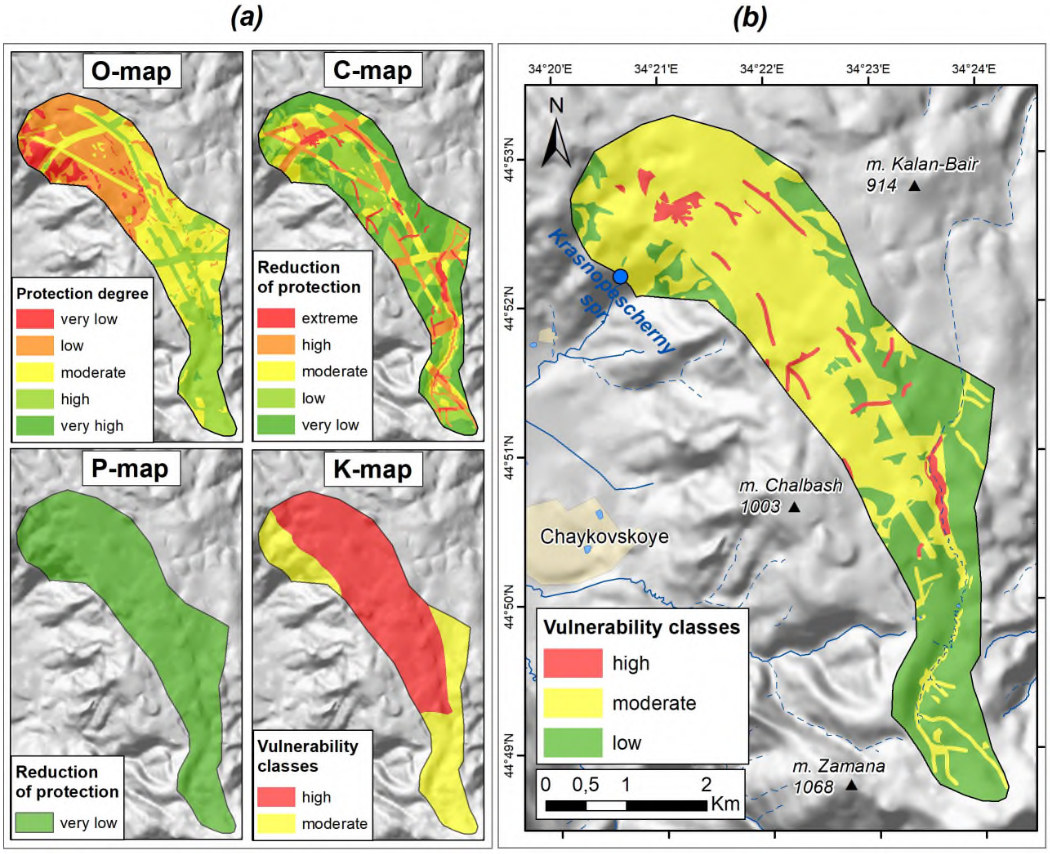

Figure 5. The maps of vulnerability factors (a) and the vulnerability map (b) of the Krasnopeshcherny karst spring.

passage of a pollutant through the phreatic zone of the massif. As a result, the zones of surface runoff sinking on the Dolgorukovskaya Yayla were classified within the high source vulnerability category.

According to the methodology being used, the source vulnerability map is derived by summing the groundwater resource vulnerability index with the K-factor index (Figure 3). The distributions of vulnerability classes for the groundwater resource and source within the assessed areas show significant differences (Figure 6). This is especially pronounced in the Ayan spring catchment, where assessment of groundwater resource vulnerability indicated more than 60% of its area in the classes of high and extreme vulnerability. Notably, the final source vulnerability map of the Ayan spring has no areas of high vulnerability at all. A similar discrepancy is also observed in the catchment of the Krasnopeshcherny spring, although to a much smaller extent.

It may be concluded, that the determining factor of the karst groundwater sources vulnerability is the development of karst conduit network in phreatic zone of the massif. The information on the hydrodynamic conditions of deep KA sections is thus critically important. It can be obtained by means of systematic groundwater tracer tests.

4.2. Application of KGV Maps for Delineation of Source Protection Zones

According to the legislation of the Russian Federation, the primary protective measure for drinking water sources is the establishment of sanitary protection zones (SPZ), which imposes a special usage regime [*Ministry of Health of the Russian Federation*, 2002]. The first (I) SPZ (strict regime) includes the territory of water intakes location and sites of all water supply facilities. The second (II) and third (III) SPZs (restriction regime) include the territory intended for protection from microbial and chemical pollutions of water supply sources, respectively. Considering the hydrogeological features of karst aquifers

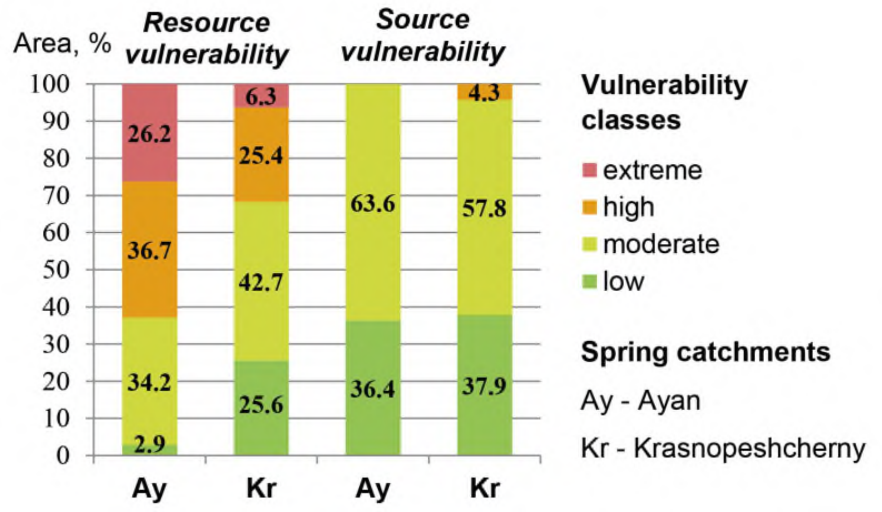

Figure 6. Distribution of source and resource vulnerability classes areas within catchments of the Ayan and Krasnopeshcherny springs.

discussed above, it is essential to differentiate normative approaches to the organization of SPZs for various types of groundwater. For example, the regulatory standards of some countries with a high proportion of karst groundwater in their water supply use specific protocols to determine protection zones for sources derived from karst aquifers [*Ravbar et al.*, 2021]. The results of the groundwater vulnerability assessment should be used as a basis. The following scheme is proposed to proceed from the source vulnerability map to the delineation of SPZs for karst water intakes (Figure 7).

According to the scheme, the I SPZ, besides the immediate vicinity of the water intake, is established within boundaries of high vulnerable areas. The II SPZ corresponds to sites of moderate groundwater vulnerability, and the III SPZ encompasses the rest of the catchment area. The main feature of this scheme is the discrete configuration of the SPZs, in contrast to the belt configuration typically used for other aquifer types. This is due to specific conditions and processes of karst aquifers recharge, including the presence of localized areas of rapid infiltration with direct connection to conduit systems. The consequence of this is the situation observed on the resulting vulnerability maps of the Ayan and Krasnopeshcherny springs, where areas remote from the intake may be more vulnerable than those close to it.

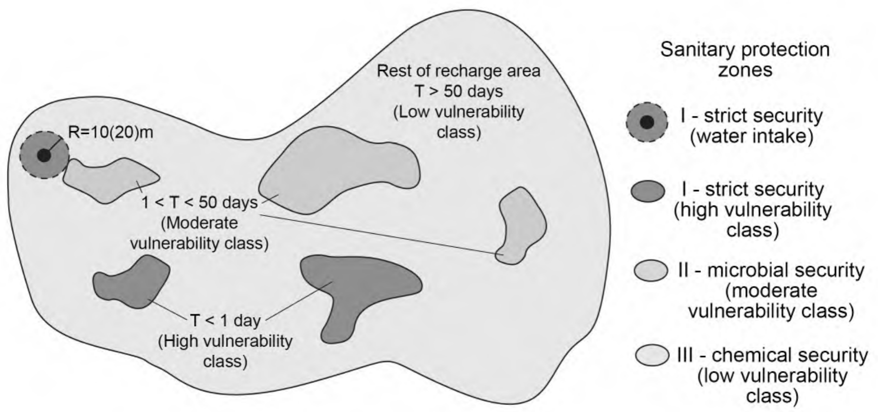

Figure 7. Conceptual scheme of an approach to delineate sanitary protection zones for karst water intakes based on a map of groundwater source vulnerability to contamination (modified after [*Brenčič et al.*, 2009] and [*Klimchouk and Tokarev*, 2014]).

5. Conclusions

The normative indicator for delineation the boundaries of sanitary protection zones for groundwater intakes is the time of its reaching by potential pollutant. Assessment and mapping of groundwater vulnerability to contamination reflects this indicator, as they are based on groundwater travel time as a key physical parameter. Thus, the groundwater vulnerability map serves as an effective tool for organizing the protection of potable water sources.

Due to the hydrogeological characteristics of karst aquifers, specialized methods are used to assess their groundwater vulnerability. To best account for regional karst features, it is often necessary to adapt and modify existing methods to regional conditions. Such modified method was developed for the Crimean Mountains region. In its extended version, it allows to perform a groundwater source vulnerability assessment, the results of which are the basis for the delineation of sanitary protection zones for karst water intakes.

The Ayan and Krasnopeshcherny karst springs, located in the central part of the Crimean Mountains, were selected as test sites for assessment of groundwater source vulnerability. Despite their geographical vicinity, the catchments of these springs are significantly different in terms of their hydrogeological conditions. This refers to both the mechanisms of karst groundwater recharge and the conditions of its transit in saturation zone. The results of vulnerability assessment of the selected springs also show substantial differences. A small portion of the Krasnopeshcherny spring catchment (about 4%) was classified as highly vulnerable, whereas no such areas were identified in the Ayan spring catchment. A common feature of the assessment results for both test sites is the predominance of the moderate vulnerability class, covering approximately 58–64% of the area, with a smaller proportion of the low vulnerability class (36–38%).

The differences identified in vulnerability assessment results are primarily due to the hydrodynamic conditions of the studied karst aquifer within the saturated zone. The KA of the Krasnopeshcherny spring exhibit a much higher groundwater flow dynamic compared to the Ayan KA. As a result, the velocities at which karst water – and consequently potential contaminants – move through the KAs differ by several times. This highlights the crucial importance of factor K in determining the vulnerability of karst groundwater sources.

We propose a scheme for transitioning from vulnerability maps to sanitary protection zones (SPZ) for karst water intakes, in accordance with the regulatory documents of the Russian Federation. According to this scheme, SPZ I is established within areas of high vulnerability, while SPZ II and SPZ III correspond to areas of moderate and low groundwater vulnerability, respectively.

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