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GEOMORPHOLOGICAL, HYDROGEOLOGICAL AND GROUNDWATER QUALITY ANALYSIS IN KARST SYSTEMS OF THE CENTRAL-WESTERN PART OF METALIFERI MOUNTAINS

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Abstract: This scientific study focuses on the relatively lesser-known karst areas in the central-western part of Metaliferi Mountains. These surfaces display pronounced spatial fragmentation, forming limestone klippes with well-defined karst systems of geomorphic and hydrogeological complexity. Using GIS and statistical methods, the study highlights the morphological and distributional traits of the identified karst forms. Additionally, the area was analysed from a hydrogeological standpoint to explore the connections between the identified insurgences and exsurgences, and the impact of the karst environment on the chemical characteristics of karst waters. The geomorphological analysis reveals a clustered and non-uniform arrangement of depression forms, as shown by the nearest neighbour index, with a quasi-circular shape highlighted by the Circularity Index. From a hydrogeological perspective, there is an increase in carbonate ions (HCO_3^-) and calcium ions (Ca^{2+}), along with a decrease in Fe and Al ions, indicating possible alluvium presence as a filter. The comparison of these values with legal thresholds demonstrates a high water quality in the analysed karst exurgences.

Key words: karst, Metaliferi Mountains, geomorphology, hydrogeology, water quality

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INTRODUCTION

The Metaliferi Mountains represent a distinct geographic unit distinguished by a significant petrographic diversity, resulting from its geological evolution, in the form of a "geosyncline trench" (Ianovici, et al., 1969). This aspect is evident in the diversity of morphogenetic processes and existing landforms within this unit. Thus, the significance of studying this territory arises from the complexity of its geographical features, which necessitates their proper utilization and preservation. This objective entails the accumulation of information from multiple perspectives that accurately reflects the field reality, thereby mitigating the degradation of existing conditions over time. However, the considerable number of studies focused on the "Golden Quadrilateral" area (Ianovici, et al., 1969) within the Metaliferi Mountains, driven by the presence of substantial and economically valuable mineral resources, has contributed to the delineation of an incomplete picture concerning this relief unit.

Consequently, the national-level study of karst, from a structural and functional perspective, has primarily been directed towards areas where karst processes are more pronounced, notably the Northern Apuseni Mountains, the eastern part of the Metaliferi Mountains (within smaller units such as the Rapolt Crystalline Island (Cocean & Buzilă, 1996) or Poieni Plateau), the Trascău Mountains, the Banat Mountains, among others. Regarding the analysed area, situated in the central-western part of the Metaliferi Mountains, west of the alignment of localities Vața de Sus – Baia de Criș – Brad – Vălișoara – Certeju de Sus, studies in the addressed domain are relatively limited in number. This is primarily due to the fragmentation of karst environments into isolated surfaces with small extensions and their spatial distribution. Some sectors within this area have been examined in a punctual manner, while others have been incorporated into more extensive scientific studies, such as those focusing on the broader spaces of the Apuseni Mountains, as found in the works of Cocean (1988; 2000). From a structural perspective, a preliminary view of the karst geomorphology in the vicinity of the locality of Băița was provided in the study written by Trufaș (1958). In the case of endokarst (cave systems), certain morphometric characteristics of caves and other cavernous features have been captured in the study of Goran (1982). Furthermore, these pieces of information are complemented by the personal contributions of speleologists, such as Gabor Halasi, in the area near the locality of Boiu de Sus (n.a.) and speleological associations. From a hydrogeological perspective, there are no representative data regarding this area due to the lack of extensive studies in this regard, resulting in diminished scientific interest. The primary work that stands out in this case, but does not cover the specific research area, was written by Orășeanu (2020).

Considering these aspects, the purpose of this scientific endeavour is to highlight the main structural and functional features of the analysed insular karst environment situated in the central-western part of the Metaliferi Mountains. This will be accomplished from a geomorphological, hydrogeological, and groundwater quality perspective. The achievement of this goal involves the following objectives:

- Analysis of karst geomorphology from a morphometric and morphological standpoint, delineating the spatial distribution of exokarstic and endokarstic forms, identifying territorial distribution patterns, and correlating them with geological features;
- Highlighting the hydrogeology of the studied area, identifying the main directions of water flow within the massifs, and outlining the primary characteristics of active cavern systems;
- Analysing the physicochemical traits of karst waters and evaluating their quality based on laboratory analyses.

In this context, the analysis has been focused on areas where karst processes are more pronounced, namely Boiu de Sus, Vața de Sus-Căzănești-Deleni, and Băița-Crăciunești.

GEOGRAPHICAL AND GEOLOGICAL SETTING

Study area location and limits

The territory analysed in this study is geographically situated within the Metaliferi Mountains, which is a component unit of the Apuseni Mountains, itself being part of the Western Romanian Carpathians. With respect to the Metaliferi Mountains, the study area is located in the central-western part, within the subunit called Masivul Măgureaua, which is "bounded by the Hălmagiu-Brad-Deva corridor to the east and the Highiş Mountains to the west" (Ianovici, et al., 1969). According to Dombay (2006), the study area falls within the Săvârşinului Mountains, "situated between the Gurahonț-Căpruța corridor to the west and the Deva-Brad corridor to the east".

The boundaries of the study area have been defined based on morpholithological criteria, primarily the presence of isolated Jurassic limestones and the morphology resulting from selective erosion, closely linked to the geological features. As a result, the analysed territory is generally delimited by the axes Vața de Sus-Zam (oriented NE-SW), Zam-Băița (oriented E-W), and Băița-Vața de Sus (oriented NW-SE), forming a configuration of discontinuous surfaces (Figure 1).

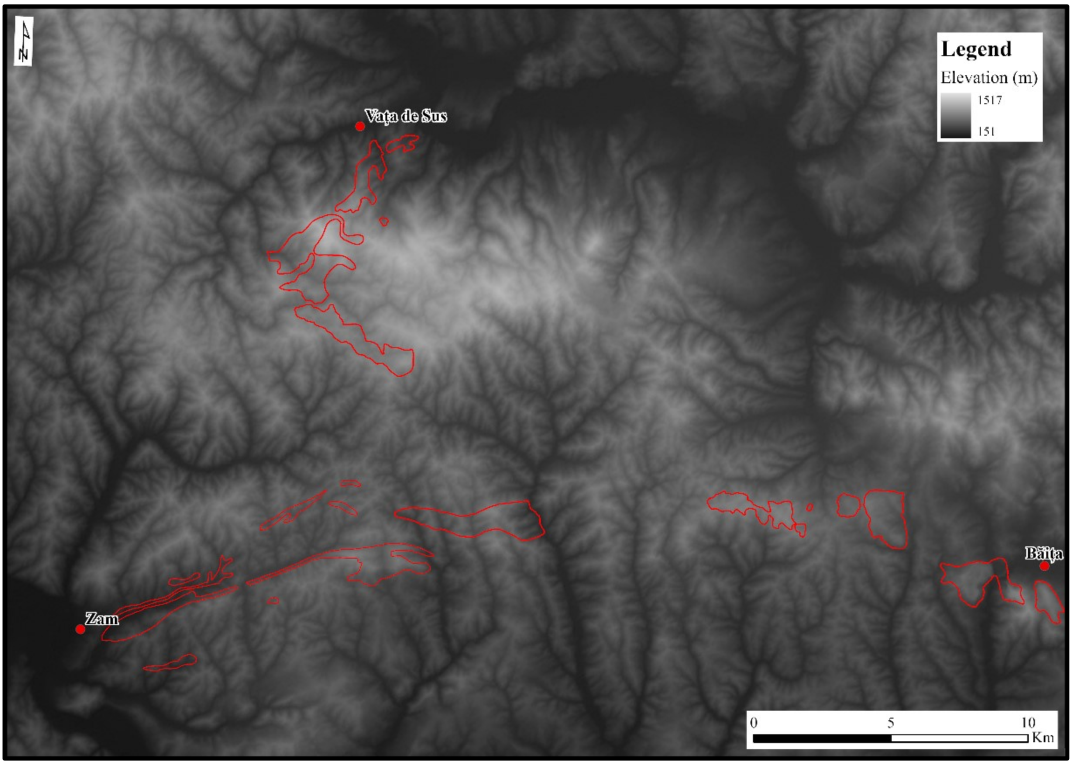

Figure 1. Study area location and limits
(Source: based on ALOS-PALSAR DEM, © JAXA/METI 2007)

Geological setting

From a geological perspective, it can be stated that the studied area is the result of a complex evolution that occurred over a relatively short period. This evolution took place in a eugeosyncline regime, characterized by intense volcanism (Ianovici, et al., 1969). Nevertheless, the exact timing of the initiation cannot be precisely determined due to the absence of sedimentary formations suitable for dating. During the Late Triassic or Early Jurassic, a system of extensional fractures developed in the basement, followed by the emplacement of ophiolitic magmas within an initial magmatic activity, leading to the formation of a rigid axial zone (Mutihac, 1990; 2007). In the Late Jurassic (Upper Dogger), the ophiolitic rock mass starts to function as a “haut-fond” with a NE-SW orientation (Ianovici, et al., 1969). With the emplacement of basic magmatites, the accumulation of Jurassic deposits began (Michetiuc, 2016) in several sedimentary areas with a trough-like character. The new Cimmerian movements led to the manifestation of central-type volcanism. Among the volcanic structures, notable ones include those located at Zam, Tămășești, and Vorța (Ianovici, et al., 1976). In the Paleocene, Laramide movements resulted in the formation of fractures that triggered intrusive magmatic activities. These Banatitic intrusions are organized in two alignments, with the eastern alignment featuring the body at Măgureaua Vaței. The emplacement of this body gave rise to thermal metamorphism phenomena, characterized by the occurrence of skarns (Ianovici, et al., 1976; Mutihac, 2007).

From a structural perspective, the analysed area comprises the following units: ophiolitic magmatites, pre-Laramide sedimentary rocks, Laramide volcanic rocks, Neogene volcanic rocks, and post-Laramide sedimentary rocks (Mutihac, 1990). These units are classified within the Western Transylvanides, a term used by Săndulescu (1984, as cited in Michetiuc, 2016) and Balintoni (1994, as cited by Michetiuc, 2016). The studied area overlaps with the Techereu-Drocea nappe, a typical obduction nappe that includes the largest ophiolitic complex in the Metaliferi Mountains. The sedimentary sequence of the nappe comprises massive Stramberg limestones of Oxfordian-Tithonian age with a reef facies, along with flishoid sandstone facies from the Eocretaceous. The continuity of the nappe is interrupted by Neogene deposits and volcanic products from the Brad Depression (Săndulescu, 1984; Mutihac, 1990).

The defining petrographic element of this territory is represented by the ophiolitic magmatites, predominantly composed of basalt flows with gabbroic intrusions, exhibiting elements typical of oceanic crust (Mutihac, 2007; Ianovici, et al., 1976). Indeed, the analysed territory comes into contact with a wide petrographic variety (Figure 2), which is also evident in the morphology of the adjacent surfaces.

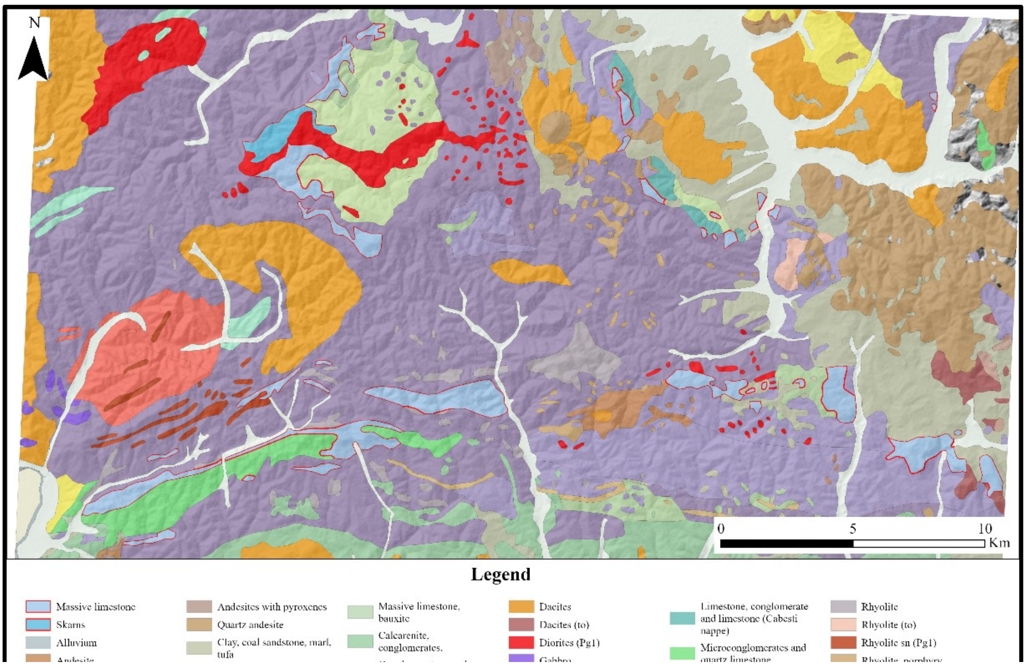

Figure 2. Lithology of the study area and the surrounding territory
(Source: based on the Geological Map of Romania, 1:200000, 1964)

According to the Geological Map of Romania at a scale of 1:200,000 (Bleahu, Savu, & Borcoș, 1964), the limestones at Vața de Sus and Vălișoara are bordered by conglomerates, calcarenites, and marly shales of Aptian age. In the southern part of the limestones in the Zam-Cărmăzănești sector, deposits of Vraconian-Cenomanian age have accumulated, consisting of microconglomerates and quartzose sandstones. The Maastrichtian is present at the contact with the limestones in the northern sector, composed of conglomerates, sandstones, and marls. The Neozoic-age magmatic body at Măgureaua Vaței consists of granites, granodiorites, and quartz-bearing diorites. This body has metamorphosed both the rocks of the basaltic complex and the existing Jurassic limestones at the contact (Ianovici, et al., 1969). Regarding the Upper Jurassic limestones, they are generally organogenic and have a thickness not exceeding 200 meters. Ghițulescu and Socolescu (1941) distinguished three horizons within these limestones:

- Oxfordian - composed of compact, reddish limestone breccias penetrated by white or reddish calcite intrusions;
- Kimmeridgian - white or whitish compact limestones with a generally larger grain size;
- Tithonian - greyish-yellow limestones with a fine structure, often crossed by calcite intrusions.

Regarding the tectonics of the studied area, the Southern Apuseni, which includes the Metaliferi Mountains, represent the suture of a mobile area that experienced a phase of crustal expansion followed by crustal shortening and the subduction of a portion of oceanic crust (Mutihac, 1990). In this area, actual thrusting phenomena are not encountered, but only underthrusting events that give the sedimentary series a monoclinal character. As a result of the Laramide tectonics, block uplift of this unit occurs (Ianovici, et al., 1969). The formations in the northern and southern rims of the Metaliferi Mountains exhibit stepped patterns, delineated by a system of fractures oriented east-west in the central part and northeast-southwest in the central-eastern part, towards the interior of the Metaliferi geosyncline. These fractures remained active during the Banatitic stage, particularly along the southern border of the Drocea ophiolitic massif. “A second system of fractures oriented northeast-southwest bounds the Poiana Ruscă Massif to the northwest and northeast, and the same direction is followed by the Banatitic alignments Săvârșin-Căzănești and Cerbia-Măgureaua Vaței” (Dombay, 2006). Regarding the area near the locality of Godinești, according to Iacob (1953), numerous fault structures can be observed at the contact between the Jurassic limestones and the northern volcanic rocks, oriented along the NE-SW direction, indicating the presence of a fault for a distance of 10 km. In several locations, significant displacements can be observed at the contact between the limestones and the Middle Cretaceous deposits, along a fault line.

The highlighting of geological features, especially those associated with tectonics, becomes even more important when the karstification process is more intense along fault alignments. Additionally, the initial configuration of the karstification environment retroactively influences this process, imprinting certain directions of karstification, which is reflected in the distribution of cavern systems and surface depressions associated with them (Šegina, 2021).

The relation between the study area and the surrounding territory

Despite their apparent isolation, especially when viewed from a structural and morphological perspective, the studied karst surfaces are related to adjacent areas, particularly from a functional standpoint. As such, the analysed karst environments are characterized by a relatively integrated relationship with the surrounding space. Considering the genesis and features of these karstic masses, both in terms of structure and functionality, their interactions with adjacent territories are complex. At the contact with non-karstifiable spaces, “perikarst zones” are formed. These perikarst zones represent transition domains between the karstic and non-karstic environments, resulting from spatial association or functional combination of the two (Goran, 2001).

The interactions with the surrounding surfaces are characterized by complementarity and reciprocity, involving the infiltration of allochthonous elements into the karst environment (rock fragments belonging to the adjacent ophiolitic complex, transported and deposited by the fluvial agent in the karst environment), and vice versa (transport and deposition of limestone fragments by the fluvial agent outside the karst domain). In the areas adjacent to the karstic masses, contact morphology has developed, including features such as karst contact depressions, blind valleys, or headless valleys.

From a hydrogeological perspective, the studied karstic masses create a discontinuity in relation to the surrounding hydrographic network, reconfiguring it in the form of disordered flow, in accordance with the existing cavity system within the massif. Allochthonous watercourses play an essential role in supplying the existing karst aquifers through ponors located at the end of blind valleys. At the base of limestone masses, the hydrographic network reorganizes, sourcing from karst springs or resurgences.

Indeed, from an altimetric perspective, in most cases, the karst domain dominates the non-karstifiable areas (a clear aspect in the sectors of Vața de Sus-Căzănești-Deleni, Boiu de Sus, and Băița-Crăciunești) due to selective erosion, forming a "Bedeleu-type" contact (Cocean, 2000), characterized by a specific morphology of residual karst, with well-defined cliffs that often overlay the geological structure boundaries (Figure 3).

Figure 3. Bedeleu type contact in Băița-Crăciunești area (Iacob, 2021)

At the base of these cliffs, a "karst contact aureole" (Cocean, 2000) develops, which is a zone varying in spatial extent, comprising fragments of rocks resulting from the disaggregation of limestones, arranged in the form of scree cones, talus slopes, or isolated blocks, with little vegetation or soil cover due to the steep slope and pronounced surface instability.

MATERIALS AND METHODS

The foundation of this endeavour was based on established principles in the field of geography, such as spatiality, causality, and the principle of integration. The process of developing the scientific work involved three main stages: firstly, the office stage, which entailed bibliographic and cartographic research, followed by fieldwork, and finally, the second office stage, involving data processing and result analysis based on the accumulated information.

During the preliminary office stage, the activity focused on delimiting the studied territory based on the Topographic Map of Romania at a scale of 1:25,000 (Military Topographic Directorate, 1957) and Geological Map of Romania at a scale of 1:200,000 (Bleahu, Savu, & Borcoş, 1964). Setting the boundaries of the area was followed by bibliographic research to establish theoretical references and organize the fieldwork. In this regard, the aforementioned maps were consulted (in the case of the topographic map, contour lines were analysed to identify inflections or discontinuities that could indicate the presence of karst elements), as well as sketches or diagrams prepared by various authors and available satellite images. These materials were supplemented by thematic, or reference bibliographic sources as mentioned before. After consulting these data sources, the points of interest that served as landmarks during field surveys were mapped using GIS programs and techniques. To facilitate efficient data management obtained during fieldwork, a database was structured, encompassing elements such as photographs, text files, and geographic data stored as "feature class" files within spatial databases.

The fieldwork took place over a period of three years, starting in 2021, between June and September and continuing each year, aiming to gather relevant data for this research. Utilizing the "Mobile Topographer" application, the position and dimensions of identified karst forms were determined in the Stereo70 coordinate system. In this case, funnel shaped, and round bottom depressions were taken into consideration, which include the ones with a closed, but also with an open upper rim. Therefore, the diameter of the identified depressions was measured from the upper rim to the opposite side of the formation. In the case of doline depth, the distance between the upper rim and the central point was considered. For endokarst, more respectively karstic cave systems, observations were made concerning speleothems, portal and gallery configurations, and the main entrance points were marked using GPS points.

Regarding the analysis of karst hydrogeology, field activities focused on identifying major karst springs and resurgences. A crucial aspect in the hydrogeological analysis involved attempting to establish underground water routes within the karst massif, connecting the springs and resurgences. A tracing method based on water conductivity, developed by the authors, and initially applied in the pilot area of Boiu de Sus, was used for this purpose, employing the Multiparameter WTW Germany Multi 350i instrument provided by the Institute for Research in Analytical Instrumentation, Cluj-Napoca. Water conductivity measurements were recorded at five-minute intervals, with values stored electronically and physically. Additionally, water samples were collected from the entry and exit points of the karst massif in 11 containers and submitted to ICIA for chemical analysis. The targeted indicators included carbonate content (HCO_3^-), calcium (Ca^{2+}), metal ions, total organic carbon (TOC), as well as nitrites (NO_2^-) and nitrates (NO_3^-) in the case of water samples from resurgences.

The geomorphological analysis of the karst terrain, which followed the fieldwork phase, began with the identification of elements that influence the karstification process and the characteristics of the surface. For this purpose, morphometric indicators such as hypsometry, slope, depth, and fragmentation density were considered, based on the ALOS-PALSAR digital elevation model with a spatial resolution of 12.5 m (ASF DAAC, 2023). Calculations were performed using ArcGIS Pro 3.1.2 and QGIS 3.28.8 software. Additionally, more complex indicators, such as the Topographic Wetness Index (TWI), were employed to highlight the relationship between terrain topography and water content, as well as moisture distribution within the study area. The integration of these morphometric parameters provided valuable insights into the geomorphic features and processes governing karst development in the analysed region (Artugyan & Urdea, 2016), along with the Terrain Ruggedness Index, proposed by Riley, DeGloria & Elliot (1999) and improved by Trevisani, Teza & Guth (2023), that reflects the heterogeneity of the surface through determining the altitude differences between the central cell of the raster file and the surrounding eight cells. The resulting values were classified using the natural breaks method. Additionally, the depressional karst forms have been analysed both individually, from a morphological perspective, and in terms of their spatial distribution, resulting in the identification of several patterns regarding the elongation degree of dolines based on the formulae of Šegina et al. (2018) and Doctor & Young (2013) (circularity and elongation indices), their orientation (from the perspective of the major axis of the ellipse framing the relief form on the horizontal plane), their density from the perspective of doline surface areas. In this regard, several indicators proposed by Šegina (2021): have been calculated: the doline density index, which represents the ratio between the doline area and the area of the Voronoi polygon it fits into, and the average nearest neighbour index, which indicates the average distance between the centroid of each doline and that of neighbouring forms, along with the Standard Deviational Ellipse.

Regarding the hydrogeological analysis, it has a preliminary nature, assuming in this case the mapping of identified insurgences and exsurgences and outlining potential connections between them. In the same context, laboratory analysis results have been correlated to highlight the way the passage through the karstic environment affects the chemical characteristics of the water, particularly the ion content. Furthermore, based on the correlation of these results with the parameter values stipulated by the current legislation (Law no. 458, 2002), water quality has been assessed in terms of compliance with the imposed thresholds.

RESULTS AND DISCUSSIONS

Karst geomorphology of the study area

The morphographic, morphometric, and positional characteristics of the relief play a decisive role in the evolution of karst, with a higher frequency of horizontal and sub-horizontal surfaces favouring the possibility of percolation of water from precipitation, thereby increasing the intensity of the karstification process (Artugyan, 2015). Regarding the hypsometry of the studied area, the values of this parameter range between 298 and 906 meters, with a range of 608 meters and an average altitude of approximately 450 meters. The higher density of sinkholes is observed in areas where the geodeclivity is lower, with the majority being in zones where slope values range from 5° to 15° (Table 1).

Table 1. Correlation between slope value and sinkhole number

Slope value	Number of sinkholes
0° – 2°	1
2° – 5°	18
5° – 10°	41
10° – 15°	35
15° – 20°	5
20° – 35°	2
>35°	0

The values of density and fragmentation depth indicate the intensity of the karstification process. According to Artugyan & Urdea (2016) there is an inverse proportional relationship between the frequency and spatial distribution of karstic forms concerning density and depth of fragmentation. This aspect is also evident in the studied area, where the fragmentation density ranges between 0 and 7.2 km/km2, and the average depth falls within the interval of 3 to 331 meters, with a range of 328 meters, typical values for mountainous regions. Depression formations are concentrated in areas with a fragmentation density of up to 3 km/km2 and a fragmentation depth not exceeding 50 meters. Concerning the slope exposure, the highest density of sinkholes overlaps with south and southwest-facing surfaces (39.25% of the total recorded forms).

In the context where the topography of the land plays a significant role in the spatial distribution of hydrological processes, as well as in the surface and subsurface flow or stagnation of waters (Sørensen, Zinko, & Seibert, 2006), through the analysis of the Topographic Wetness Index (TWI) calculated for the studied area, higher values are observed in the case of river valleys and karst plateaus, such as those in the sectors of Boiu de Sus, Vața de Sus-Căzănești-Deleni, or Băița-Crăciunești. There is a higher concentration of sinkholes in areas with moderate to high moisture levels. The values of the Terrain Roughness Index (TRI), when correlated with the positions of the identified sinkholes, indicate their concentration on flat or nearly horizontal surfaces, where surface roughness is reduced, in the case of karst plateaus, compared to areas where this indicator shows moderate to high values (Figure 4). However, given the DEM resolution, the results may not represent the surface accurately. In this case, a model with a higher resolution, preferably computed using LiDAR point clouds would be more appropriate.

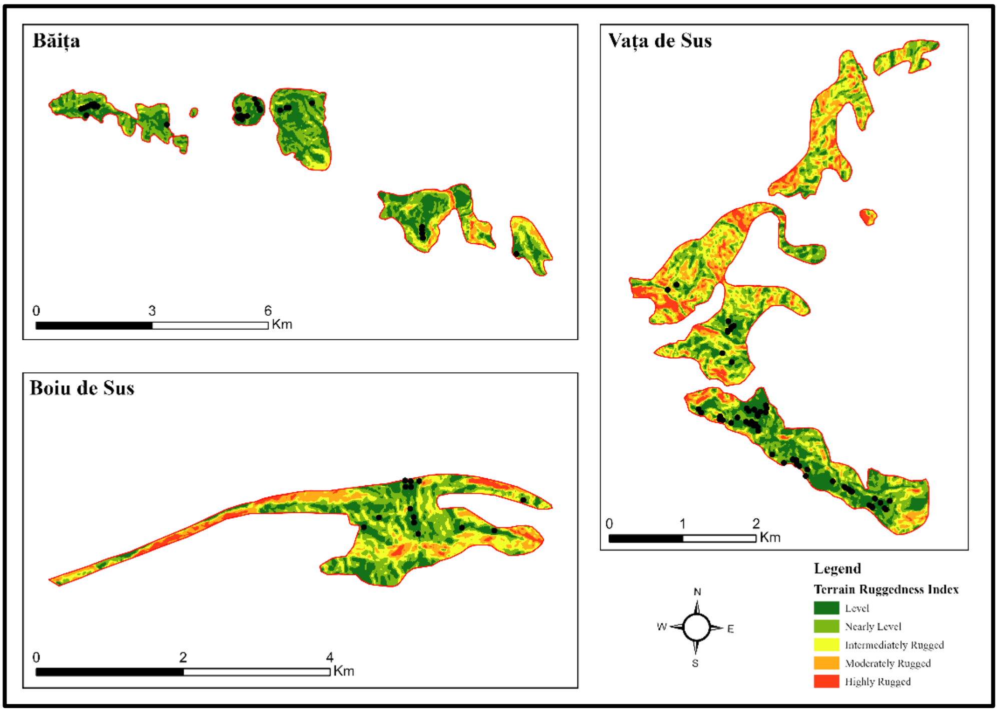

Figure 4. Terrain Ruggedness Index correlated with the existing sinkholes in the study area (Source: Iacob, 2023; Includes Material © JAXA/METI 2007)

From a morphometric and morphological standpoint, the identified depressional forms, diagnostic for karst relief, according to Ford and Williams (2007) , largely exhibit a quasi-circular configuration, resulting from the dissolution process. Additionally, their appearance is generally symmetrical, conical, with a rounded lower part, indicating sediment accumulation. Analysing these formations dimensionally, it is evident that their depth is in all cases smaller than their diameter, suggesting a higher intensity of lateral corrosion compared to vertical dissolution. Furthermore, the statistical distribution of the surface areas and perimeters of the identified dolines (Table 2) does not follow a normal distribution, as it is positively skewed (skewness of 5.32), with a predominance of dolines with reduced surface areas. The degree of dispersion of values around the mean is higher, as highlighted by the elevated value of the standard deviation.

Table 2. Sinkhole area and perimeter statistics

	Minimum	Maximum	Mean	Std. dev.
Perimeter (m)	17.30	556.187	128.03	84.45
Area (m^2)	29.09	22,100.66	1,751	3,318.91

The circularity and elongation indices could be calculated using the formula proposed by Šegina et al. (2018) due to the sub-circular configuration of the dolines and the tendency towards centricity. The circularity index in this case shows a shape of the sinkholes close to the circular one, which signals a higher efficiency and duration of karstification and generally the lack of specific morphogenetic conditions. On the contrary, the only case that highlights a difference in regard to the circularity index is N-S oriented Boiu de Sus doline valley, with formations that follow the same direction (Figure 5). This is an indicator of the fault that presumably conditioned the formation of these dolines.

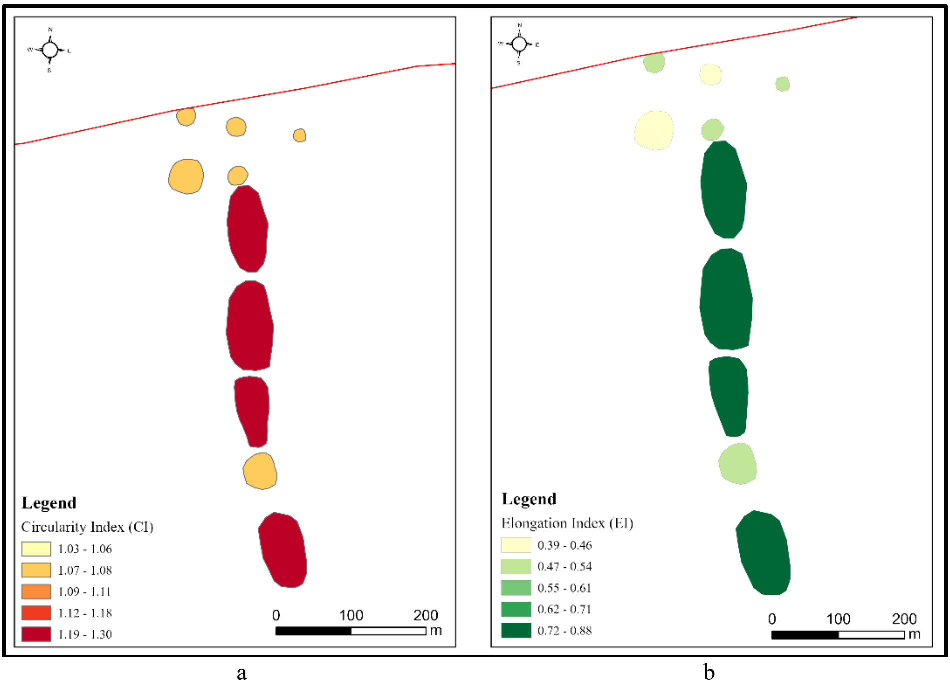

Figure 5. Circularity index (a) and Elongation Index (b) calculated for Boiu de Sus doline valley

In the case of the Vața de Sus-Căzănești-Deleni sector, the depressional forms exhibit an almost circular configuration, with an average Circularity Index value of 1.08, and the calculated values show a relatively normal distribution. The Elongation Index records values with a slightly positive distribution (skewness of 1.14), and the average value is 0.54. The predominant orientation of the forms in the area is E-W, consistent with the overall morphology. Regarding the Vălișoara-Băița sector, there is a higher dispersion of Elongation Index values, with an average of 0.54 and a slightly positive distribution. The general orientation of the individual forms in this sector is SW-NE, and the asymmetry is low, with average Circularity Index values of 1.07. The distribution of identified forms, analysed using the Density Index (Šegina, 2021),-relative to the surface area of dolines, reflects a higher concentration of these forms in the Vața de Sus-Căzănești-Deleni sector, with an average value of 0.04. These surfaces represent 2.73% of the total extension of the sector. In the case of the Boiu de Sus and Băița sector, the density of forms is lower, with Density Index values of 0.04 (1.6% of the total surface area) and 0.02 (0.4% of the sector's extension), respectively. The degree of doline concentration, directly related to the aforementioned indicator, highlighted by the Nearest Neighbour Index (Table 3), shows that in almost all situations, dolines tend to be grouped in clusters, more pronounced in the Băița and Vața de Sus-Căzănești-Deleni areas. Thus, based on these aspects, it is observed that the karstification process is not generalized throughout the study area, and there is a tendency for the forms to concentrate in smaller areas.

Table 3. Indicators concerning the distribution of dolines in the study area

Sector	Density Index	Doline area (m²)	Percentage of total area	Nearest neighbour index	Distribution
Vața de Sus-Deleni	0.04	94,876	2.73	0.57	Clustered
Boiu de Sus	0.04	54,505	1.6	0.85	Random
Băița	0.02	37,708	0.4	0.49	Clustered

Furthermore, the karstification process follows certain directions, some of which are evident, as in the case of the Vața de Sus-Căzănești-Deleni sector, where the identified forms have a general orientation along the NW-SE direction. Equally apparent is the distribution direction of the forms in the Boiu de Sus area, which is oriented N-S. However, the tendency of doline distribution in the Băița area is less observable. The statistically highlighted direction, indicated by the calculated parameter, is WNW-ESE.

The endokarst is closely related to the exokarstic forms, sharing the same morphogenetic conditions at its base. Regarding the studied area, it can be observed that the endokarst has a smaller extent, with poorly developed forms (small cave dimensions). The main endokarstic form consists of caves with a single level and few ramifications. This situation is explained by the limited volume of karstifiable rocks and their isolated distribution in the territory. Moreover, the length of the galleries is limited, with the maximum recorded in Peștera de Sus de la Godinești, measuring 279 m (Goran, 1982), and the maximum level difference reaching 27 m in Peștera de Deasupra Casei lui Sârbu (Goran, 1982). The cave entrances are generally enlarged as a result of the breakdown process of limestone and can be found both at the base of the massifs and suspended on slopes, mainly near the limit of the study area (Figure 6).

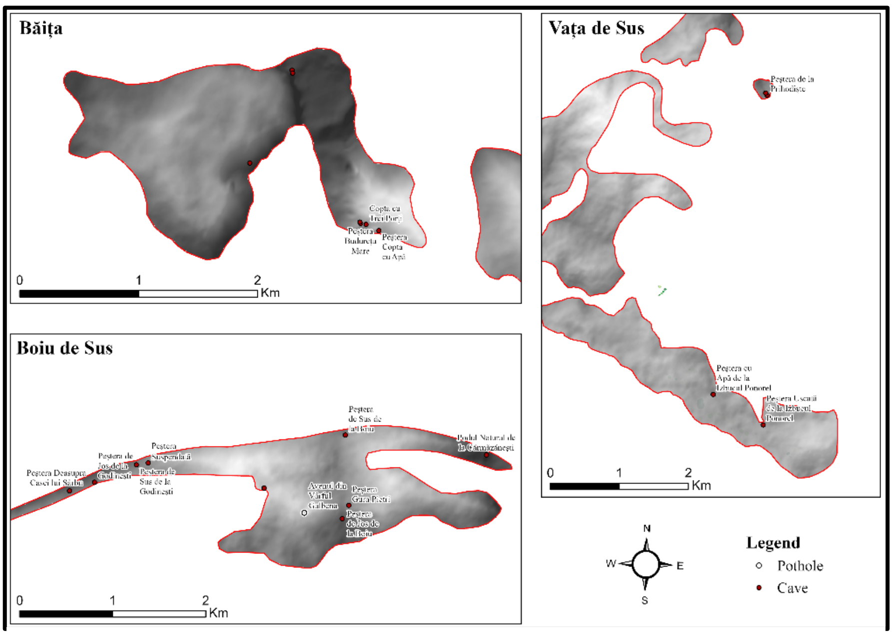

Figure 6. Cave locations in the study area
(Data source: Halasi, n.a; Goran, 1982; Includes Material © JAXA/METI 2007)

Speleothems are present, mainly concretionary forms such as stalactites, draperies, and corrosion forms like natural chimneys or hieroglyphs. Concerning the hydrological regime of the identified caves and shafts, some of them are active, being continuously traversed by watercourses. On the other hand, numerous fossil, inactive caves have been observed.

Karst hydrogeology and water quality

Considering the configuration of the analysed area as sectors with a smaller volume of karstifiable rocks, the water circulation within the existing massifs exhibits certain characteristics. The arrangement of narrow ridges or isolated massifs has not favoured the development of extensive karst aquifers. However, water circulation within the karst massif can be ascertained through the presence of karst springs (insurgences) and karst exsurgences (Figure 7).

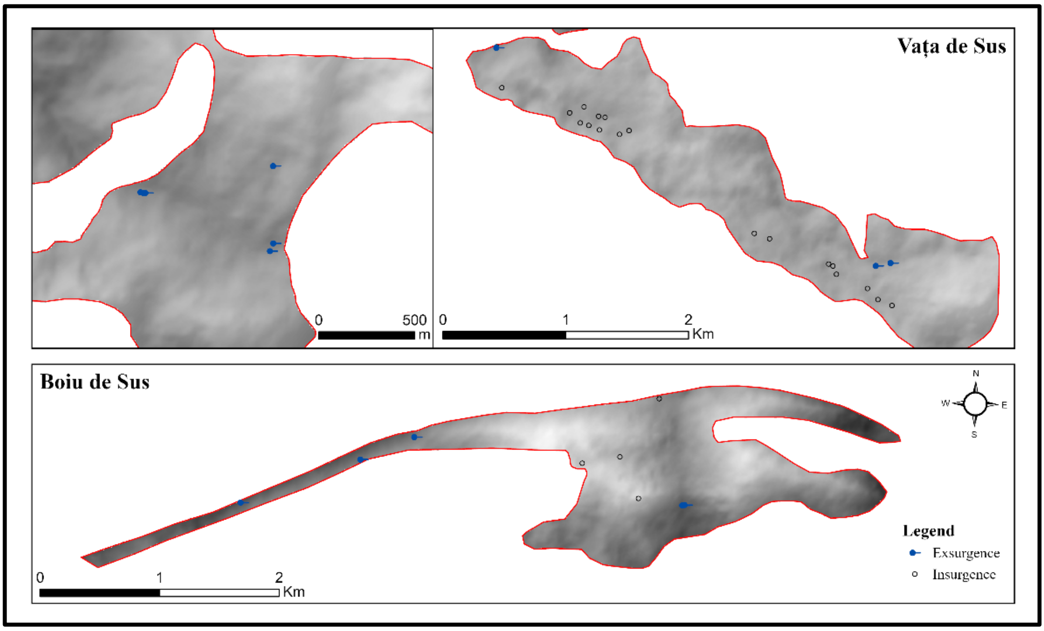

Figure 7. Insurgence and exsurgence distribution in the study area
(Source: Iacob, 2023 Includes Material © JAXA/METI 2007)

Analysing the spatial distribution of sinkholes and springs within the sectors of the studied area, along with the surface morphology, it is evident that, from a hydrogeological perspective, the karstic area of Boiu de Sus exhibits a relatively better-defined karst network compared to the Vața de Sus-Căzănești-Deleni sector. This can be primarily attributed to the orientation of this sector along the NW-SE direction, which has favoured the development of localized drainage systems at shorter distances. The water circulation within the Boiu system most likely corresponds to the “standard model” of karst aquifers (White, 2019) , with the network characterized by a concentration of runoff in the central part, aligned with the valley of dolines that follows the same pattern.

Therefore, considering the overall morphology of the Boiu de Sus sector and the distribution of sinkholes and springs, it can be assumed that an underground network of the dendritic type, according to White's typology (2019) was formed. This network is characterized by the delineation of a primary underground course with the presence of secondary branches. Additionally, after measuring the discharge rates, a significant difference is observed between the values of this parameter at the main identified inlet point (sinkhole at the base of the Boiu Upper Cave), approximately 1-2 l/s, and the exit points, the spring at the Boiu Lower Cave (about 5-6 l/s), and the nearby resurgence (approximately 30 l/s). Based on this discrepancy, it can be presumed that there are other sources supplying these springs with higher flow rates.

Regarding the existing underground connections, based on the available data mentioned above, along with the water conductivity within the two nearby resurgences (with a difference of approximately 100 $\mu S/cm^{-1}$), it can be reasonably asserted that there is a connection between Peștera de Jos de la Boiu and the resurgence associated with Peștera de Sus de la Boiu. Additionally, it is assumed that there is a connection between the Avenul din Vârful Galbena and the spring at Peștera de Jos de la Boiu (Figure 8). Furthermore, the authors consider that despite the proximity between the two springs, the connection between them is limited.

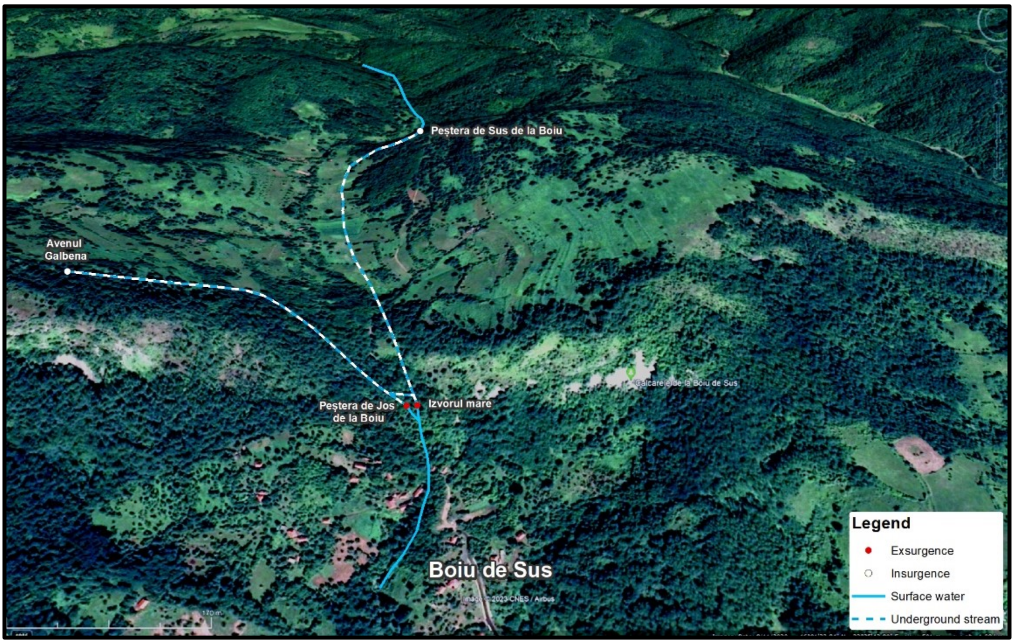

Figure 8. Possible links between the main insurgence and exsurgence points in Boiu de Sus area

Regarding the tracing of these underground courses, the authors have developed a method based on conductivity, which was applied for the first time in the Boiu de Sus area. However, this method requires further adjustments of the involved parameters and application in various contexts. The results will be detailed in future works.

In case of the chemical characteristics of water and how they are influenced by the passage through the karst environment, it is observed that there is a modification resulting in either an increase or decrease in the content of existing ions (Table 4).

Table 4. Chemical changes between insurgence and exsurgence points in the study areas

Indicators	U.M.	Water sample collection points			
		Boiu insurgence	Boiu spring	Vața insugence	Vața spring
HCO_3^-	mg/l	204	332	262	286
Ca^{2+}	mg/l	36	87	50	61
TOC	mg/l	7	1.7	4.5	1.8
Al	µg/l	8.1	4.1	7.8	4.3
Fe	µg/l	18	9.1	5.1	4.4

For this example, only the significant changes were selected, along with the representative ions for the karst medium. The sectors in which these analyses were conducted are Boiu de Sus and

Vața de Sus-Căzănești-Deleni areas. More specifically, the water samples in the Boiu de Sus sector were collected from the large spring located in the vicinity of the Boiu Lower Cave and the resurgence situated at the base of the Peștera de Sus de la Boiu. In the Vața de Sus sector, the samples were taken from two points approximately 150 m apart on the ground surface, towards its eastern part.

The recorded changes in these parameters follow a consistent trend in both sectors, characterized by an expected increase in the quantity of carbonate ions (HCO_3^-) and calcium ions (Ca^{2+}), as a consequence of calcite dissolution. Additionally, a reduction is noted in the amount of organic matter (TOC) as well as aluminium and iron ions. It is presumed that this reduction can be attributed to the presence of alluvium in the subterranean water path, acting as a filter. Another aspect deducible from the modifications in these parameters, when comparing the two sectors, is the manner in which the intensity of changes is directly proportional to the distance and duration of traversing the karst environment. Consequently, it is evident that the water ion content has been significantly more altered in the Boiu de Sus sector compared to the Vața de Sus sector.

Comparing the quantities of ions in the water from the analysed karstic springs, it is observed that they do not exceed the thresholds set by the law (Law no. 458, 2002), being well below these values (Table 5). Thus, the water quality from the examined sources is high, and it is suitable for domestic consumption.

Table 5. Comparison between water quality threshold and analysed spring values

Indicators	Threshold	U.M.	Boiu cave spring	Boiu spring*	Vața spring
Al	200	µg/l	4.1	4.1	7.8
Fe	200	µg/l	7.3	9.1	5.1
Mn	50	µg/l	<1	1	<1
Zn	5,000	µg/l	2.1	1.7	2.9
Pb	10	µg/l	<1	<1	<1
Nitrates (NO_3^-)	50	mg/l	2.35	4.14	-
Nitrites (NO_2^-)	0.5	mg/l	<0.05	<0.05	-
Ni	20	µg/l	<1	<1	<1

Note: *The spring is located in the vicinity of Peștera de Jos de la Boiu

Along with these parameters, in all cases there is also a decrease in the total organic content, highlighting the purifying effect that the karst environment has on the circulating water.

CONCLUSIONS

The karst processes manifested in the Metaliferi Mountains, and implicitly in the studied area, are characterized by a smaller extent compared to other areas, such as the northern part of the Apuseni Mountains (Northern Apuseni). The reduced scale of this phenomenon can be attributed to the smaller volume of karstifiable rocks in this region, along with the limited extension of limestone-covered surfaces and their dispersed distribution in the territory, presenting themselves as smaller limestone massifs.

The comprehensive investigation of the karst geomorphology and hydrogeology in the mountainous region under study has provided insights into the intricate nature of karst processes and their interactions with the surrounding territory. From a geomorphological perspective, the study area exhibits a diverse range of karstic landforms, predominantly characterized by quasi-circular depressional features with conical morphology. Sinkholes tend to concentrate on flat or nearly horizontal surfaces, such as karst plateaus, with reduced surface roughness. The analysis of morphometric parameters, including circularity and elongation indices, further supports the presence of dominant directional patterns in karst development and the role of tectonic conditions in karst formation.

The hydrogeological analysis highlights, in some cases, the existence of a well-defined karst network, connected to the surface via insurgences and exsurgences. Boiu de Sus sector exhibits a relatively complex underground network, characterized by a dendritic drainage pattern. Based on the available data, the authors proposed possible links between those points in the aforementioned sector. However, further investigations are needed to refine the tracing method based on conductivity and to prove the existence of underground connections within the karst network. The chemical analysis of water samples collected from karst springs indicates modifications in ion content due to the dissolution of calcite and filtration through alluvium. Notably, the water quality remains high, meeting regulatory standards for domestic use.

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