Carpathian Journal of Earth and Environmental Sciences August 2025 Vol. 20, No. 2, p. 323 – 332; DOI:10.26471/cjees/2025/020/336

ASSESSING ROCK GLACIERS' WATER STORAGE IN THE SOUTHERN CARPATHIANS

Oana BERZESCU[1,2], Petru URDEA[1,2*], Florina ARDELEAN[2] & Andrei IONIȚĂ[1,2]

[1]Institute for Advanced Environmental Research, West University of Timisoara, Timișoara, Romania; oana.berzescu@e-uvt.ro; andrei.ionita@e-uvt.ro

[2]Department of Geography, West University of Timișoara, Timișoara, Romania; petru.urdea@e-uvt.ro; florina.ardelean@e-uvt.ro

[*]Corresponding author: petru.urdea@e-uvt.ro

Abstract: This study provides the first estimate of the water volume equivalent (WVEQ) of ground ice in intact rock glaciers within the Southern Carpathians, based on an ice content range of 10 % to 20 %. The research focuses 48 intact rock glaciers, most of which are located in the Retezat Mountains. Using existing geophysical measurements, the ice content was determined to range between 10 % and 20 %, representing the first attempt to estimate WVEQ at such a low ice content. Using the thickness-to-area scaling method, subsurface ice volumes were estimated and converted to WVEQ using an ice density factor of 0.9 g/cm^3. The results show that the total estimated water volume ranges from 0.009 km^3 at 10 % ice content to 0.014 km^3 at 15 %, and 0.018 km^3 at 20 %. The largest water volumes are stored in the rock glaciers of the Retezat Mountains, with most of the water concentrated between elevations of 2000 and 2200 m elevation, in north-facing valleys underlain by granite bedrock. The study highlights the critical role of lithology, orientation, and elevation in permafrost preservation in mid-latitude mountains. The findings emphasize that while the water equivalent in intact rock glaciers within marginal periglacial environments is relatively low, their hydrological and ecological significance should not be underestimated, particularly in the context of climate change and permafrost degradation. Significant changes in mountain stream runoff, along with a notable decline in the biodiversity of rock glaciers, are expected to occur within this century at high altitudes in the Southern Carpathians.

Keywords: rock glaciers, ice content, water volume equivalent, marginal periglacial environment, Southern Carpathians

1. INTRODUCTION

Climate change is reshaping the availability and quality of water resources in the cryosphere (Hock et al., 2019). Globally, high mountain regions contain glaciers, ice caps, snow and permafrost, acting as vital freshwater reserves for billions of people (Viviroli et al., 2020). Glaciers and permafrost are forecasted to decline considerably as global temperatures rise throughout this century (Beniston et al., 2018). Permafrost ice within rock glaciers is suggested to be more resilient to warming climates than glacier ice, thanks to the coarse debris cover shielding it (Wagner et al., 2021). However, recent studies revealed that rapid warming led to permafrost degradation in high mountains (Biskaborn et al., 2019; Etzelmüller et al., 2023; Noetzli et al., 2024). The melting of ice in rock glaciers - mainly, the cementation ice - affects runoff patterns and water quality (Williams et al., 2006; Thies et al., 2013; Brighenti et al., 2024), and can also influence slope stability and rock masses (Barsch, 1996).

Rock glaciers are impressive features of periglacial landscapes found extensively in the world`s cold mountains (Kääb, 2013). The classification of rock glaciers into active, inactive and relict landforms depends on their dynamic state and internal ice presence (Barsch, 1996). Rock glaciers with internal ice, whether active or inactive, are referred to as intact rock glaciers (Seppi et al., 2012; Onaca et al., 2017a) and are considered water reservoirs in high mountains (Wagner et al., 2020). The amount and properties of runoff from high-mountain watersheds can be affected

by the abundance and presence of intact rock glaciers over time (Arenson et al., 2022).

Rock glaciers in the Southern Carpathians were recently studied regarding their existence (Urdea, 1988, 1992) and their distribution and extent (Onaca et al., 2017a). However, there is a lack of understanding regarding the hydrological significance of rock glaciers in this mountain range (Onaca, 2017). The Carpathians are a crucial area for periglacial research, as permafrost occurs under marginal conditions here (Popescu et al., 2024). Recent geophysical investigations revealed that the ice content in intact rock glaciers of the Southern Carpathians is relatively low (< 20 %) (Onaca et al., 2025). In contrast, in many other mountainous regions, the ice content of rock glaciers typically ranges between 40 % and 60 % (Hausmann et al., 2012; Krainer & Ribis, 2012; Rangecroft et al., 2015; Wagner et al., 2021). This paper aims to estimate the water storage capacity of intact rock glaciers in the Southern Carpathians using empirical equations and to analyze the spatial distribution of their water volume equivalents.

2. STUDY AREA

The Southern Carpathians stretch 250 kilometers from east to west, featuring the highest peaks in the Romanian Carpathians, with elevations reaching up to 2500 meters, with 14 peaks higher than 2500 m. The predominant lithology consists of granitoids and metamorphic rocks. Around 15 % of their total area is defined by alpine periglacial conditions (Onaca et al., 2017b). At elevations above 2100 meters, the mean annual air temperature is negative, and annual precipitation amount averages approximately 1000 mm. In these high-altitude regions, freezing occurs on more than 200 days/year and snow covers the ground for over six months (Onaca, 2017). Currently, the Southern Carpathians do not contain any surface glaciers, ice masses, or perennial snow patches (Urdea et al., 2022). However, during the cold phases of the Holocene, small glaciers likely occupied high-altitude cirques in the Southern Carpathians (Urdea et al., 2024).

Present-day climatic conditions enable the persistence of isolated permafrost in areas particularly conducive to its preservation (Popescu et al., 2024). As a result, permafrost is confined to sites above 2000 m, typically found in areas with openwork debris landforms, such as rock glaciers and coarse talus deposits. These locations are characterized by limited income of solar radiation, persistent snow cover during the summer months and highly efficient cooling of the coarse deposits (Onaca et al., 2015).

In high mountain regions, the most visible expression of permafrost is rock glaciers. Onaca et al. (2017a) inventoried 306 rock glaciers in the Southern Carpathians, covering a total area of 12.7 km^2. Most of these rock glaciers are relict, with only 16 % still containing internal ice. Intact rock glaciers are found only in four massifs, all above 2400 meters: Retezat, Făgăraș, Parâng, and Iezer (Onaca et al., 2017a) (Figures 1-2). Of these, 77 % are located in granites and granodiorites (Onaca et al., 2017a). The Retezat Mountains have the highest number (94) and density (0.52 landforms/km^2) of rock glaciers in the Southern Carpathians, and it is here that the longest rock glacier is found, stretching 1.4 km (Onaca et al., 2017a).

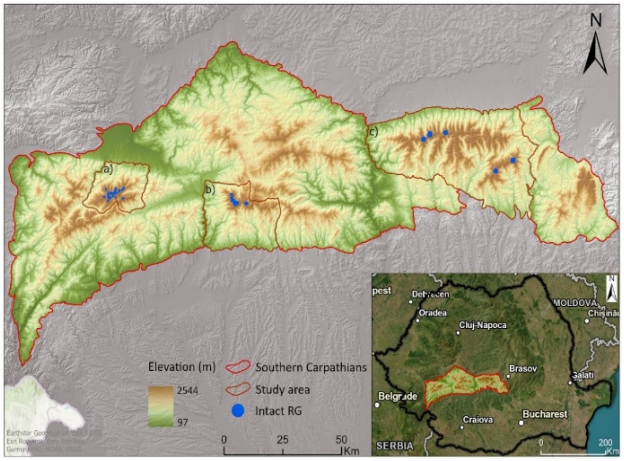

Figure 1. Distribution of intact rock glaciers (RG) across Southern Carpathians (Romania): a) Retezat Mountains, b) Parâng Mountains and c) Făgăraș-Iezer Mountains. The insert map highlights the location of the study area in Romania.

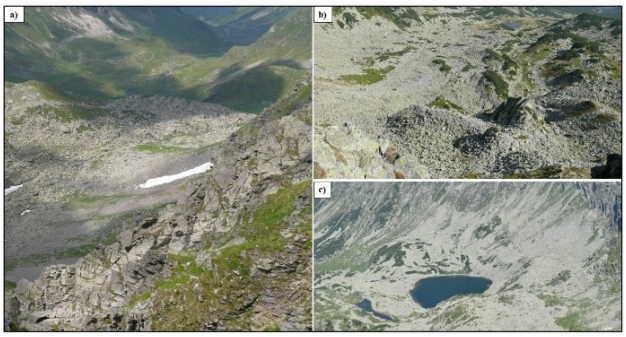

Figure 2. Pictures of the rock glaciers in the Southern Carpathians: (a) Făgăraș; (b) Retezat; (c) Parâng.

3. MATERIAL AND METHODS

3.1. Estimating water storage in intact rock glaciers

For this study we utilized the rock glacier polygons of the Southern Carpathians from the extensive inventory compiled by Onaca et al. (2017a). Rock glaciers were mapped in this inventory through

a combination of field surveys and detailed analysis of high-resolution aerial images (Onaca et al., 2017a). The classification of rock glaciers either as intact or relict was based on morphological characteristics along with additional ground-based measurements, such as geophysical surveys, ground surface temperature readings and velocity measurements using satellite images (Necsoiu et al., 2016a; Onaca et al., 2025). Since only 48 rock glaciers are classified as intact in this inventory, we estimated the water volume equivalent (WVEQ) of ice content exclusively for these landforms. Of the 48 intact rock glaciers, 30 are located in the Retezat Mountains and 11 in the Parâng Mountains, primarily on granitoid and granite bedrock. About 15 % of the intact rock glaciers are found on crystalline schists, mainly in the Făgăraș and Iezer Mountains. The majority of rock glaciers in the Southern Carpathians are associated with talus slopes and are classified as talus rock glaciers, while 26 % have primarily evolved from glacial deposits and are categorized as debris rock glaciers (Barsch, 1996). Rock glaciers were divided into two geometric categories: lobate and tongue - shaped. A length-to-width ratio was employed to differentiate between the two, with lobate glaciers having a ratio less than 1 and tongue-shaped glaciers exceeding 1 (Giardino & Vick, 1987).

3.2. Rock glacier water storage estimation

Rock glaciers can contain water in the form of perennially frozen permafrost, seasonally frozen water in the active layer, or perennially unfrozen taliks where they are present. In this study we estimated only the water equivalent of perennially frozen permafrost. To estimate the calculation of the water volume equivalent for intact rock glaciers in the Southern Carpathians we employed the thickness-to-area scaling method (Brenning, 2005). In the absence of comprehensive subsurface datasets, researchers commonly use empirical thickness-area relationships to determine rock glacier thickness and volume (Brenning, 2005; Wagner et al., 2021; Li et al., 2024; Pandey et al., 2024). To estimate the subsurface ice volumes of rock glaciers (RGV), the method proposed by Brenning (2005) calculates the product of mean thickness (MT), surface area (SA), and ice content (IC) for each rock glacier, as described in Eq. (1). These values are converted to water volume equivalent (WVEQ) by applying an ice density factor of 0.9 g/cm^3 (900 kg/m^3) (Paterson, 1994).

$$RGV = MT \times SA \times IC \quad (1)$$

The empirical relationship utilized in this study calculates the average thickness of rock glaciers (MT) as a function of their surface area (S) in km^2, incorporating a scaling parameter c = 50 and a scaling exponent β = 0.2, as explained below (Brenning, 2005):

$$MT = c \times S^{\beta} \quad (2)$$

Because rock glaciers do not consist entirely of ice, an average ice content ranging between 40 % and 60 % is commonly used to estimate WVEQ (Hausmann et al., 2012; Rangecroft et al., 2015). To account for the possibility of decreased ice content in inactive rock glaciers in the Austrian Alps, Wagner et al. (2021) adjusted the lower limit to 20 %. Recent geophysical investigations conducted in the Southern Carpathians indicate a low ground ice content, typically ranging between 10 - 20 %, in rock glaciers located in the Retezat and Făgăraș Mountains (Onaca et al., 2025). Based on these findings, we approximated the WVEQ for the Southern Carpathians using a lower bound of 10 %, a mean value of 15 % and an upper bound of 20 % for ice content.

4. RESULTS

Intact rock glaciers in the Retezat Mountains account for 76 % of the total surface area of all intact rock glaciers in the Southern Carpathians. The average area of intact rock glaciers in the Retezat Mountains is 0.072 km^2, compared to 0.049 km^2 in the Parâng Mountains and 0.018 km^2 in the Făgăraș-Iezer Mountains. The largest intact rock glacier, located in the Retezat Mountains, spans an area of 0.41 km^2 and measures 1.4 km in length and 400 m in width.

In terms of coverage, intact talus rock glaciers occupy an area of 1.56 km^2, while intact debris rock glaciers cover 1.26 km^2. The elevation of intact rock glaciers across the study area ranges from 1866 m to 2272 m. Among the mountain ranges, the Parâng Mountains have the lowest mean elevation for intact rock glaciers (2106 m), while the Făgăraș-Iezer Mountains have the highest (2160 m) (Table 1). Of the intact rock glaciers, 6.25 % are situated at mean elevations between 1800 and 2000 m, 83.33 % between 2000 and 2200 m, and 10.42 % above 2200 m. The maximum elevation of 2272 m is found in the Retezat Mountains. Although lobate rock glaciers account for 60 % of the total number of intact rock glaciers, they cover a cumulated area of only 1.14 km^2, whereas tongue-shaped rock glaciers span 1.68 km^2. Of the intact rock glaciers, 77 % are located in areas with granites and granodiorites, 17 % on schists and paragneisses and 6 % on amphibolites. The total cumulative volume of intact rock glaciers in the Southern Carpathians, estimated using the thickness-to-area scaling method, is 0.0903 km^3 (Table 2). Of

Table 1. Characteristics of the intact rock glaciers in the Southern Carpathians.

Mountain range	No. of IRG	Total area of IRG (km^2)	Mean area of IRG (km^2)	Mean elevation of IRG (m)	No. of talus IRG	No. of debris IRG	No. of lobate IRG	No. of tongue-shaped IRG
Retezat	30	2.15	0.07	2133	24	6	17	13
Parâng	11	0.54	0.05	2106	8	3	6	5
Făgăraș-Iezer	7	0.13	0.02	2160	7	-	6	1
TOTAL	48	2.82	0.06	2131	39	9	29	19

IRG = intact rock glaciers

Table 2. Total cumulative volume of intact rock glaciers in the Southern Carpathians.

Mountain range	Total Volume (km^3)	Average Volume (km^3)	Volume of talus IRG	Volume of debris IRG	Volume of lobate IRG	Volume of tongue-shaped IRG
Retezat	0.0688	0.0024	0.0359	0.0353	0.0283	0.0429
Parâng	0.0174	0.0014	0.0059	0.0097	0.0041	0.0115
Făgăraș- Iezer	0.0041	0.0005	0.0035	-	0.0008	0.0027
All	0.0903	0.0019	0.0453	0.0450	0.0332	0.0571

IRG = intact rock glaciers

this total, the Retezat Mountains contribute 0.0688 km^3, the Parâng Mountains account for 0.0174 km^3, and the Făgăraș-Iezer Mountains contribute 0.0041 km^3. The average volume of intact rock glaciers in the Southern Carpathians is 0.0019 km^3, with the highest values observed in the Retezat Mountains (0.0024 km^3) and the lowest in the Făgăraș-Iezer Mountains (0.0005 km^3). The volume of intact talus rock glaciers is comparable to that of debris rock glaciers. The cumulative volume of intact rock glaciers is 0.082 km^3 between 2000 and 2200 m, with only 7.09 % of total volume located below 2000 m and 1.87 % above 2200 m. Additionally, 0.055 km^3 of the total volume of intact rock glaciers is associated with north-facing rock glaciers. Only four intact rock glaciers have a volume exceeding 0.005 km^3, all of which are located in the Retezat Mountains (Figure 3a).

The WVEQ in the Southern Carpathians was estimated using average ice content of 10 % (lower bound), 15 % (mean value) and 20 % (upper bound) (Figure 4a). The analysis revealed that intact rock glaciers in the Southern Carpathians had an estimated WVEQ of 0.018 km^3 at 20 %, 0.014 km^3 at 15 % and 0.009 km^3 at 10 %. Rock glaciers in the Retezat Mountains contain 76 % of the total water volume stored in intact rock glaciers (Figure 3b).

Assuming an ice content estimate of 15 %, talus rock glaciers are estimated to contain a water volume of 0.0072 km^3, while debris rock glaciers retain 0.0064 km^3. In the Retezat Mountains, 0.0054 km^3 of water is estimated to exist in talus rock glaciers and 0.0049 km^3 in debris rock glaciers (Figure 5d). Using the same ice content assumption, Figure 5a indicates that 0.0122 km^3 of WVEQ is stored in intact rock glaciers located between 2000 - 2200 m, 0.0010 km^3 in those below 2000 m, and 0.0003 km^3 in rock glaciers above 2200 m. Most intact rock glaciers host a water volume

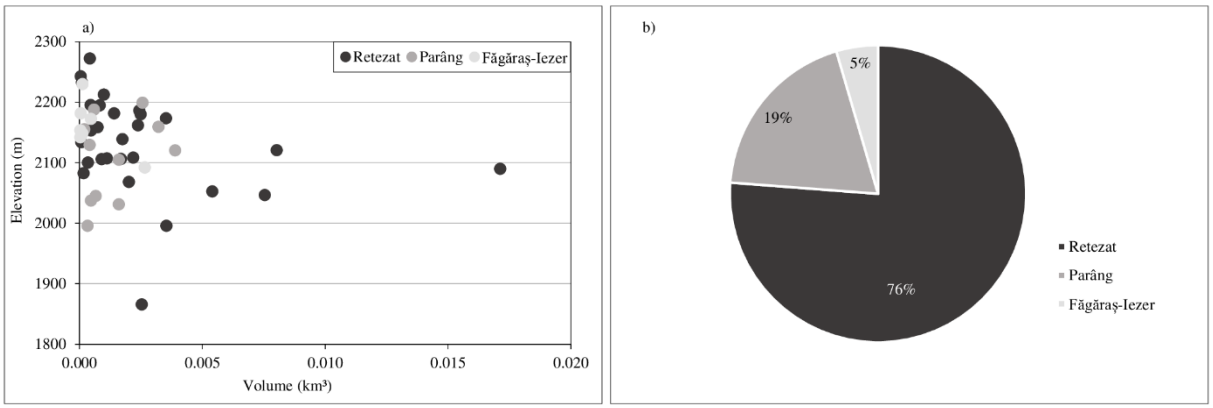

Figure 3. Distribution of intact rock glaciers volumes by elevation (a) along with the percentage of total cumulative volume (b) in the Retezat, Parâng and Făgăraș Mountains.

a)

Mountain range	WVEQ (km³)		
	20%	15%	10%
Retezat	0.014	0.010	0.007
Parâng	0.003	0.003	0.002
Făgăraș-Iezer	0.001	0.001	0.000
All	0.018	0.014	0.009

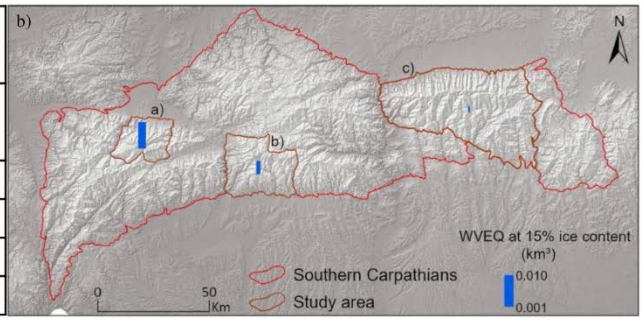

Figure 4. Water volume equivalent in the Southern Carpathians using a range of 10 - 20 % ice content (table) (a) and distribution of ice water volume equivalent at 15 % ice content (b).

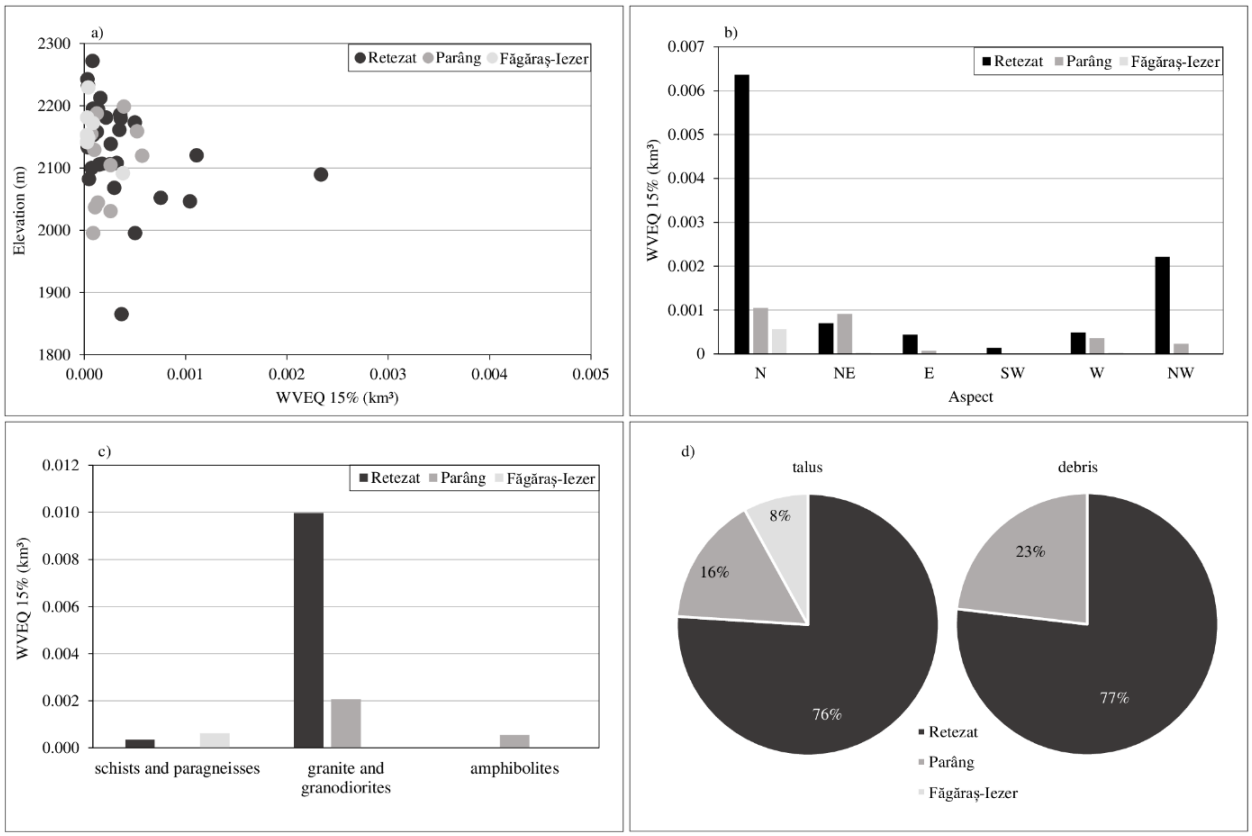

Figure 5. The estimation of WVEQ at 15 % ice content across elevation (a), aspect (b) and lithology (c) along with the percentage of water equivalent in talus and debris rock glaciers (d).

smaller than 0.001 km^3, with the highest values recorded in the Retezat Mountains. Regarding their orientation, 0.0064 km^3 of water is estimated to be stored in north-facing rock glaciers and 0.002 km^3 in those with a northwest-facing aspect (Figure 5b).

Furthermore, 0.0120 km^3 of water is associated with intact rock glaciers in granite and granodiorite lithologies while only 0.0015 km^3 is found on schists, paragneisses and amphibolites (Figure 5c).

Figure 6a presents the spatial distribution of the water volume equivalent (WVEQ) in the Retezat Mountains, based on an assumed ice content of 15 %. The highest water volumes are predominantly associated with north-facing rock glaciers, including Valea Rea, Pietrele and Galeșu. The Valea Rea rock glacier has the highest water volume equivalent (WV), estimated at 0.002335 km³. Notably, five rock glaciers in the Retezat Mountains contain over 0.000499 km^3 of water stored in ground ice. The total WVEQ for intact rock glaciers in the Retezat Mountains is estimated at 0.010 km^3. The intact rock glaciers in the Retezat Mountains have a corresponding water volume equivalent (WVEQ) between 0.000031 km^3 and 0.002335 km^3. In the Parâng Mountains, only two out of 11 intact rock glaciers have a WVEQ exceeding 0.000498 km^3, while the majority are classified within the lowest WVEQ range (0.000025 - 0.000498 km^3) (Figure 6b). In the Făgăraș-Iezer Mountains, the WVEQ ranges from 0.0000253 km^3 to 0.0003796 km^3 (Figure 6c).

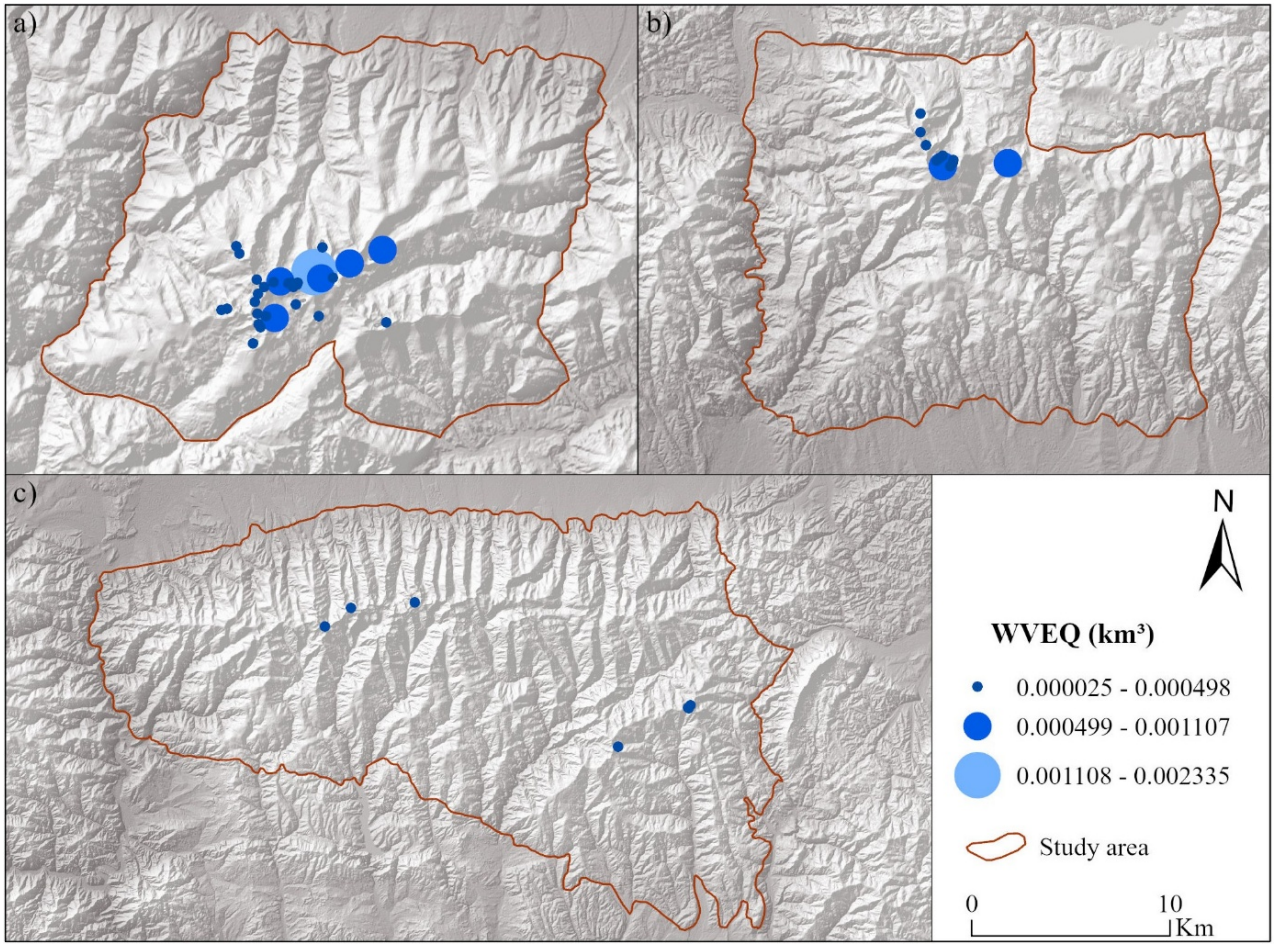

Figure 6. Distribution of WVEQ for intact rock glaciers at 15 % ice content in the Retezat (a), Parâng (b) and Făgăraș-Iezer (c) Mountains.

5. DISCUSSION

Rock glaciers have attracted significant scientific attention in recent decades, particularly regarding their geomorphology and climatic implications (Haeberli et al., 2006). However, relatively few studies have investigated the hydrology of rock glaciers (Arenson et al., 2022), especially their water volume equivalent (WVEQ). Many of these studies rely on empirical approaches, often without prior data on the ice content of rock glaciers in specific regions. While most research on discontinuous permafrost has estimated WVEQ using an ice content range of 40 - 60 % (Barsch, 1996; Brenning, 2005; Hausmann et al., 2012; Rangecroft et al., 2015; Abdullah & Romshoo, 2024), recent studies have adjusted the lower bound to 20 % (Wagner et al., 2021; Pandey et al., 2024). Recent geophysical investigations in the Southern Carpathians, however, reveal even lower ice content in marginal periglacial intact rock glaciers (Onaca et al., 2025). In the study by Onaca et al. (2025) ice content was estimated using the petrophysical joint inversion (PJI) method (Wagner et al., 2019). This approach combines the inversion of electrical resistivity tomography and refraction seismic tomography datasets to determine the distribution of ice, water, rock, and air within the substrate (Mollaret et al., 2020). Using the PJI method, the study estimated ice content in the Southern Carpathians rock glaciers to range between 10 % and 20 %. These findings are consistent with earlier studies by Onaca et al. (2013a, 2013b, 2015), which also indicated reduced ice content in several rock glaciers across the Retezat, Parâng, and Făgăraș Mountains, based on geophysical measurements. This research provides the first estimates of water volume equivalent (WVEQ) for the region, utilizing an ice content range of 10 - 20 %.

The total estimated water volume stored in intact rock glaciers of the Southern Carpathians is significantly smaller compared to other periglacial regions. This discrepancy is primarily attributed to the thin frozen layers of these rock glaciers, which typically measure less than 10 m, as demonstrated by previous geophysical studies (Onaca et al., 2013a, 2013b, 2015; Popescu et al., 2015). These thin, deforming frozen layers result in extremely low surface displacement rates, ranging from a few millimeters to 5 cm per year, as observed in the rock glaciers of the Retezat Mountains (Onaca et al., 2025).

Furthermore, these rock glaciers feature a relatively thick active layer, measuring 5 - 10 meters (Onaca et al., 2013a, 2013b, 2015, 2025; Popescu et al., 2017), which underscores the marginal nature of permafrost conditions in the Southern Carpathians.

The higher density of rock glaciers within granitic and granodioritic bedrock contributes significantly to the greater total ice storage in the Retezat and Parâng Mountains compared to the Făgăraș-Iezer Mountains. 89 % of the estimated water volume in intact rock glaciers is in granitic and granodioritic bedrock, highlighting the crucial role lithology plays in permafrost preservation at the edge of its occurrence. Another important factor is orientation, with 88.8 % of the total volume of water stored in intact rock glaciers located in the northern quadrant (N, NW and NE). Elevation also influences the distribution of the WVEQ, with 90.4 % of the total water found in rock glaciers between 2000 and 2200 m. A roughly equal amount of water is stored in talus and debris rock glaciers, with 0.0071598 km^3 in talus rock glaciers and 0.0063861 km^3 in debris rock glaciers. Although fewer in number, tongue-shaped rock glaciers retain more water (0.008286 km^3) compared to lobate rock glaciers (0.005259 km^3).

At high altitudes, mountain permafrost is especially sensitive to notable atmospheric warming (Gruber & Haeberli, 2009). A decline in ground ice content within rock glaciers can lead to permafrost degradation, characterized by volume loss and the development of thermokarst features. Large thermokarstic depressions have been observed in the Southern Carpathians and are associated with inactive rock glaciers (Onaca et al., 2013a; Necsoiu et al., 2016a). Following the complete melting of internal ground ice, the resulting relict rock glaciers retain water only in seasonally frozen or perennially unfrozen states. Analyzing the evolution of glacial lakes in the Retezat Mountains, Necsoiu et al. (2016b) concluded that, in some cases, changes in the ground ice content of rock glaciers can contribute to the short-term evolution of these water bodies.

Multiple studies have highlighted the importance of rock glaciers in sustaining downstream runoff (Tenthorey, 1992; Duguay et al., 2015; Rogger et al., 2017). In catchments with rock glaciers in the Southern Carpathians, runoff typically peaks in late spring and early summer due to snow and ice melt combined with high precipitation. It then gradually declines through late summer and autumn, reaching minimal flow in winter. According to a study by Geiger et al. (2014), a comparison of hydrographs from two catchments - one containing rock glaciers and the other without - revealed that stormflow from rock glaciers contributes significantly to total catchment runoff (15 - 30 %). Additionally, in catchments with rock glaciers, flood peaks occur later following rainfall events but tend to be higher in magnitude. According to climate projections (Hock et al., 2019), rising air temperatures will continue through the end of the century, leading to a further decline in permafrost in the Southern Carpathians. This warming trend is expected to affect mountain stream runoff, potentially causing streams to dry up or flow intermittently in the coming decades. To gain a deeper understanding of the hydrological role of permafrost in mountain streams, we plan to expand our observations by incorporating discharge monitoring and hydrochemical measurements to identify the water sources.

Cold rocky landforms play a vital role as climate refugia for both terrestrial and aquatic species in mountain ecosystems (Brighenti et al., 2021). A wide variety of microbes, plants, and animals rely on cold habitats like rock glaciers for their survival (Hotaling et al., 2019). Recent studies have shown that high-altitude springs emerging from cold landforms have been warming at a rate of 0.2 °C per year over the past decade (Lencioni et al., 2022). Although there may be a delay in the response of these warming waters to changes in cold-adapted organisms, shifts in community composition are expected within this century (Fahy et al., 2024). Permafrost degradation in the Southern Carpathians over the coming decades will intensify the stress on the biodiversity of cold-water habitats. Further investigations into the thermal regime of spring water and the monitoring of cold-adapted communities in these cold springs are crucial, especially in protected areas like Retezat National Park.

Quantifying the water volume stored in ground ice is crucial for Retezat National Park environment in the context of rising air temperatures. This information is essential for the effective management of this protected area, which is part of the UNESCO Biosphere Reserve network, given its importance for conserving diverse habitats, rich biodiversity, and remarkable landscapes. These results are valuable for understanding the impacts of climate change on mountainous regions characterized by marginal permafrost conditions.

6. CONCLUSIONS

The first estimation of water equivalent of ground ice within intact rock glaciers in the Southern Carpathians revealed a total water volume ranging from 0.009 to 0.018 km^3. This research approximated the water volume equivalent for rock glaciers in the Southern Carpathians using a lower bound of 10 %, a mean value of 15 % and an upper bound of 20 % for ice content. The highest water volumes are stored in

the intact rock glaciers of the Retezat Mountains (76 %), followed by 19 % in the Parâng Mountains and 5 % in the Făgăraș-Iezer Mountains.

Between 2000 and 2200 m, the retained water volume ranges from 0.00002 km^3, assuming a lower bound of 10 % ice content, to 0.00311 km^3, assuming an upper bound of 20 % ice content. The intact rock glaciers situated in granitic and granodioritic bedrock accounts for 89 % of the estimated water volume, highlight the critical role of lithology in permafrost preservation in marginal periglacial regions, determining factor for the establishment of open works structures. This creates conditions for the chimney effect and the Balch effect manifestation, through which the cementing ice in these structures is formed and maintained. Most of the water is stored in large, north-facing rock glaciers in the Retezat Mountains. The total water storage in talus and debris rock glaciers is nearly equivalent. This study emphasizes that, although the water equivalent in intact rock glaciers within marginal periglacial environments is relatively low, its significance for hydrological and ecological functions should not be overlooked.

As global temperatures rise due to climate change, permafrost degradation in the Southern Carpathians is projected to intensify, leading to significant changes in stream runoff patterns in the region. Permafrost thawing is expected to cause a decline in cold-adapted organisms.

Acknowledgement

This research was funded by a grant from the Ministry of Research, Innovation and Digitization, CNCS - UEFISCDI, under project number PN-IV-P2-2.1-TE-2023-0603, within PNCDI IV.

Additionally, this article was supported by the UVT 1000 Develop Fund of the West University of Timisoara.

REFERENCES

Abdullah, T. & Romshoo, S.A., 2024**.** *A Comprehensive Inventory, Characterization, and Analysis of Rock Glaciers in the Jhelum Basin, Kashmir Himalaya, Using High-Resolution Google Earth Data.* Water, 16(16), 2327, https://doi.org/10.3390/w16162327.

Arenson, L.U., Harrington, J.S., Koenig, C.E.M. & Wainstein, P.A., 2022. *Mountain Permafrost Hydrology—A Practical Review Following Studies from the Andes.* Geosciences, 12(2), 48, https://doi.org/10.3390/geosciences12020048.

Barsch, D., 1996. *Rockglaciers. Indicators for the Present and Former Geoecology in high mountain environments*. Springer, Berlin, 131.

Beniston, M., Farinotti, D., Stoffel, M., Andreassen, L. M., Coppola, E., Eckert, N., Fantini, A., Giacona, F., Hauck, C., Huss, M., Huwald, H., Lehning, M., López-Moreno, J.-I., Magnusson, J., Marty, C., Morán-Tejéda, E., Morin, S., Naaim, M., Provenzale, A., Rabatel, A., Six, D., Stötter, J., Strasser, U., Terzago, S. & Vincent, C., 2018. *The European Mountain cryosphere. a review of its current state, trends, and future challenges.* The Cryosphere, 12(2), 759–794, https://doi.org/10.5194/tc-12-759-2018.

Biskaborn, B.K., Smith, S.L., Noetzli, J., Matthes, H., Vieira, G., Streletskiy, D.A., Schoeneich, P., Romanovsky, V.E., Lewkowicz, A.G., Abramov, A., Allard, M., Boike, J., Cable, W.L., Christiansen, H.H., Delaloye, R., Diekmann, B., Drozdov, D., Etzelmüller, B., Grosse, G., Guglielmin, M., Ingeman-Nielsen, T., Isaksen, K., Ishikawa, M., Johansson, M., Johannsson, H., Joo, A., Kaverin, D., Kholodov, A., Konstantinov, P., Kröger, T., Lambiel, C., Lanckman, J.-P., Luo, D., Malkova, G., Meiklejohn, I., Moskalenko, N., Oliva, M., Phillips, M., Ramos, M., Sannel, A.B.K., Sergeev, D., Seybold, C., Skryabin, P., Vasiliev, A., Wu, Q., Yoshikawa, K., Zheleznyak, M. & Lantuit, H., 2019. *Permafrost is warming at a global scale.* Nature Communications, 10(1), 264, https://doi.org/10.1038/s41467-018-08240-4.

Brenning, A., 2005. *Climatic and geomorphological controls of rock glaciers in the Andes of Central Chile: Combining Statistical Modelling and Field Mapping*. Humboldt Universitat zu Berlin, Berlin, Germany, https://doi.org/10.18452/15332.

Brighenti, S., Hotaling, S., Finn, D.S., Fountain, A.G., Hayashi, M., Herbst, D., Saros, J.E., Tronstad, L.M. & Millar, C.I., 2021. *Rock glaciers and related cold rocky landforms: Overlooked climate refugia for mountain biodiversity*, Global Change Biology, 27 (8), 1504–1517, https://doi.org/10.1111/gcb.15510.

Brighenti, S., Colombo, N., Wagner, T., Pettauer, M., Guyennon, N., Krainer, K., Tolotti, M., Rogora, M., Paro, L., Steingruber, S.M., Del Siro, C., Scapozza, C., Sileo, N.R., Villarroel, C.D., Hayashi, M., Munroe, J., Liaudat, D.T., Cerasino, L., Tirler, W., Comiti, F., Freppaz, M., Salerno, F., Litaor, M.I., Cremonese, E., di Cella, U.M. & Winkler, G., 2024. *Factors controlling the water quality of rock glacier springs in European and American mountain ranges.* Science of The Total Environment, 953, 175706, https://doi.org/10.1016/j.scitotenv.2024.175706.

Duguay, M.A., Edmunds, A., Arenson, L.U. & Wainstein, P.A., 2015. *Quantifying the Significance of the Hydrological Contribution of a Rock Glacier - A Review*, Conference: GEOQuébec 2015. 68th Canadian Geotechnical Conference, 7th Canadian Permafrost Conference, Quebec, QC, Canada.

Etzelmüller, B., Isaksen, K., Czekirda, J., Westermann, S., Hilbich, C. & Hauck, C., 2023. *Rapid warming and degradation of mountain permafrost in Norway and Iceland*. The Cryosphere, 17(12), 5477-5497, https://doi.org/10.5194/tc-17-5477-2023.

Fahy, J.C., Demierre, E. & Oertli, B. 2024. *Long-term monitoring of water temperature and*

macroinvertebrates highlights climate change threat to alpine ponds in protected areas. Biological Conservation, 290, 110461, https://doi.org/10.1016/j.biocon.2024.110461.

Geiger, S.T., Daniels, J.M., Miller, S.N. & Nicholas, J.W., 2014. *Influence of rock glaciers on stream hydrology in the La Sal Mountains, Utah*. Arctic, Antarctic, and Alpine Research, 46 (3), 645–658, 10.1657/1938-4246-46.3.645.

Giardino, J. & Vick, S., 1987. *Geologic engineering aspects of rock glaciers.* In: Giardino, J. Shroder, J., Vitek, J. (Eds.), *Rock Glaciers*. Allen and Unwin, London, pp. 265–287.

Gruber, S. & Haeberli, W., 2009. Mountain *Permafrost.* Springer, Permafrost Soils, Soil Biology, 16, 33-44, 10.1007/978-3-540-69371-0.

Haeberli, W., Hallet, B., Arenson, L., Elconin, R., Humlum, O., Kääb, A., Kaufmann, V., Ladanyi, B., Matsuoka, N., Springman, S. & Vonder Mühll, D., 2006. *Permafrost creep and rock glacier dynamics.* Permafrost and Periglacial Processes, 17(3), 189–214, http://dx.doi.org/10.1002/ppp.561.

Hausmann, H., Krainer, K., Brückl, E. & Ullrich, C., 2012. *Internal structure, ice content and dynamics of Ölgrube and kaiserberg rock glaciers (Ötztal Alps, Austria) determined from geophysical surveys.* Austrian Journal of Earth Sciences, 105 (2), 12–31, http://hdl.handle.net/20.500.12708/164869.

Hock, R., Rasul, G., Adler, C., Cáceres, B., Gruber, S., Hirabayashi, Y., Jackson, M., Kääb, A., Kang, S., Kutuzov, S., Milner, Al., Molau, U., Morin, S., Orlove, B. & Steltzer, H. 2019. *High Mountain Areas.* In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [Pörtner, H.-O., Roberts, D.C., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E., Mintenbeck, K., Alegría, A., Nicolai, M., Okem, A., Petzold, J., Rama, B. & Weyer, N.M. (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 131–202, https://doi.org/10.1017/9781009157964.004.

Hotaling, S., Foley, M.E., Zeglin, L.H., Finn, D.S., Tronstad, L.M., Giersch, J.J., Muhlfeld, C.C. & Weisrock, D.W. 2019. *Microbial assemblages reflect environmental heterogeneity in alpine streams.* Global Change Biology, 25(8), 2576 - 2590, https://doi.org/10.1111/gcb.14683.

Krainer, K. & Ribis, M., 2012. *A rock glacier inventory of the Tyrolean Alps (Austria).* Austrian Journal of Earth Sciences, 105 (2), 32–47.

Kääb, A., 2013. *Rock Glaciers and Protalus Forms.* In: Elias, S.A., Mock, C.J. (Eds.), Encyclopedia of Quaternary Science (Second Edition), Elsevier, Amsterdam, pp. 535–541, https://doi.org/10.1016/B978-0-444-53643-3.00104-7.

Lencioni, V., Stella, E., Zanoni, M.G. & Bellin, A., 2022. *On the delay between water temperature and invertebrate community response to warming climate.* Science of the Total Environment, 837, 155759, https://doi.org/10.1016/j.scitotenv. 2022.155759.

Li, M., Yang, Y., Peng, Z. & Liu, G., 2024. *Assessment of rock glaciers, water storage, and permafrost distribution in Guokalariju. Tibetan Plateau*. The Cryosphere, 18, 1–16, https://doi.org/10.5194/tc-18-1-2024.

Mollaret, C., Wagner, F.M., Hilbich, C., Scapozza, C. & Hauck, C., 2020. *Petrophysical Joint Inversion Applied to Alpine Permafrost Field Sites to Image Subsurface Ice, Water, Air, and Rock Contents.* Frontiers in Earth Science, 8, https://doi.org/10.3389/feart.2020.00085.

Necsoiu, M., Onaca, A., Wigginton, S. & Urdea, P., 2016a. *Rock glacier dynamics in Southern Carpathian Mountains from high-resolution optical and multi-temporal SAR satellite imagery.* Remote Sensing of Environment, 177, 21–36, https://doi.org/10.1016/j.rse.2016.02.025.

Necsoiu, M., Mîndrescu, M., Onaca, A. & Wigginton, S., 2016b. *Recent morphodynamics of alpine lakes in Southern Carpathian Mountains using high-resolution optical imagery.* Quaternary International, 415, 164-174, https://doi.org/10.1016/j.quaint.2015.12.032.

Noetzli, J., Isaksen, K., Barnett, J., Christiansen, H.H., Delaloye, R., Etzelmüller, B., Farinotti, D., Gallemann, T., Guglielmin, M., Hauck, C., Hilbich, C., Hoelzle, M., Lambiel, C., Magnin, F., Oliva, M., Paro, L., Pogliotti, P., Riedl, C., Schoeneich, P., Valt, M., Vieli, A. & Phillips, M., 2024. *Enhanced warming of European mountain permafrost in the early 21st century.* Nature Communications, 15, 10508, https://doi.org/10.1038/s41467-024-54831-9.

Onaca, A.L., Urdea, P., & Ardelean, A.C., 2013a. *Internal structure and permafrost characteristics of the rock glaciers of Southern Carpathians (Romania) assessed by geoelectrical soundings and thermal monitoring.* Geografiska Annaler: Series A, Physical Geography, 95(3), 249–266, https://doi.org/10.1111/geoa.12014.

Onaca, A.L., Urdea, P., Ardelean, A.C., & Serban, R., 2013b. *Assessement of internal structure of periglacial landforms from Southern Carpathians (Romania) using DC resistivity tomography*. Carpathian Journal of Earth and Environmental Sciences, *8 (2), 113-122*, https://www.researchgate.net/publication/257939601.

Onaca, A., Ardelean, A.C., Urdea, P., Ardelean, F., & Sîrbu, F., 2015. *Detection of mountain permafrost by combining conventional geophysical methods and thermal monitoring in the Retezat Mountains, Romania.* Cold Regions Science and Technology 119, 111–123, https://doi.org/10.1016/j.coldregions.2015.08.001.

Onaca, A., 2017. *Periglacial Processes and Landforms from Southern Carpathians: Geomorphological and Geophisical Approac.* West University of Timisoara (in Romanian).

Onaca, A., Ardelean, F., Urdea, P. & Magori, B., 2017a. *Southern Carpathian rock glaciers: Inventory, distribution and environmental controlling factors.* Geomorphology, 293, 391-404, http://dx.doi.org/10.1016/j.geomorph.2016.03.032.

Onaca, A., Urdea, P., Ardelean, A.C., Șerban, R. & Ardelean, F., 2017b. *Present-day periglacial processes in the alpine zone.* In Rădoane, M.,

Vespremeanu-Stroe, A. (Eds.), *Landform dynamics and evolution in Romania*. Springer, 147-176, doi: 10.1007/978-3-319-32589-7_7.

Onaca, A., Sîrbu, F., Poncos, V., Hilbich, C., Strozzi, T., Urdea, P., Popescu, R., Berzescu, O., Etzelmüller, B., Vespremeanu-Stroe, A., Vasile, M., Teleagă, D., Birtaș, D., Lopătiță, I., Filhol, S., Hegyi, A. & Ardelean, F., 2025. *Slow-moving rock glaciers in marginal periglacial environment of Southern Carpathians.* EGUsphere, https://doi.org/10.5194/egusphere-2024-3262.

Pandey, P., Ali, S.N., Das, S.S. & Khan, M.A.R., 2024. *Rock glaciers of the semi-arid northwestern Himalayas: distribution, characteristics, and hydrological significance*. Catena, 238, 107845, https://doi.org/10.1016/j.catena.2024.107845.

Paterson, W.S.B., 1994. *The Physics of Glaciers, Butterworth-Heinemann*, Oxford, 480 pp.

Popescu, R., Vespremeanu-Stroe, A., Onaca, A. & Cruceru, N., 2015. *Permafrost in the granitic massifs of Southern Carpathians (Parâng Mountains).* Zeitschrift für Geomorphologie, 59(1), 1-20, doi.org/10.1127/0372-8854/2014/0145.

Popescu, R., Onaca, A.L., Urdea, P. & Vespremeanu-Stroe, A., 2017. *Spatial distribution and main characteristics of alpine permafrost from Southern Carpathians.* In Rădoane, M., Vespremeanu-Stroe, A. (Eds.). *Landform dynamics and evolution in Romania*. Springer, 117-146, doi: 10.1007/978-3-319-32589-7_6.

Popescu, R., Filhol, S., Etzelmüller, B., Vasile, M., Pleșoianu, A., Vîrghileanu, M., Onaca, A., Șandric, I., Săvulescu, I., Cruceru, N., Vespremeanu-Stroe, A., Westermann, S., Sîrbu, F., Mihai, B., Nedelea, A. & Gascoin, S., 2024. *Permafrost Distribution in the Southern Carpathians, Romania, Derived from Machine Learning Modeling*. Permafrost and Periglacial Processes, 35(3), 243–261, https://doi.org/10.1002/ppp.2232.

Rangecroft, S., Harrison, S. & Anderson, K., 2015. *Rock Glaciers as Water Stores in the Bolivian Andes: An Assessment of Their Hydrological Importance*. Arctic, Antarctic, and Alpine Research 47 (1), 89–98, https://doi.org/10.1657/AAAR0014-029.

Rogger, M., Chirico, G.B., Hausmann, H., Krainer, K., Brückl, E., Stadler, P. & Blöschl, G., 2017. *Impact of mountain permafrost on flow path and runoff response in a high alpine catchment.* Water Resources Research, 53 (2), 1288–1308, https://doi.org/10.1002/2016WR019341.

Seppi, R., Carton, A., Zumiani, M., Dall'Amico, M., Zampedri, G. & Rigon, R., 2012. *Inventory, distribution and topographic features of rock glaciers in the southern region of the Eastern Italian Alps (Trentino).* Geografia Fisica e Dinamica Quaternaria, 35(2), 185–197, http://dx.doi.org/10.4461/GFDQ.2012.35.17.

Tenthorey, G., 1992. *Perennial névés and the hydrology of rock glaciers.* Permafrost and Periglacial Processes, 3 (3), 247–252, https://doi.org/10.1002/ppp.3430030313.

Thies, H., Nickus, U., Tolotti, M., Tessadri, R. & Krainer, K., 2013. *Evidence of rock glacier melt impacts on water chemistry and diatoms in high mountain streams.* Cold Regions and Technology, 96, 77-85, https://doi.org/10.1016/j.coldregions.2013.06.006.

Urdea, P., 1988. *Consideraţii asupra formării gheţarilor de pietre din Munţii Retezat*, Stud. cerc. geol., geofiz., geogr., Geografie, XXXV, 85-90.

Urdea, P., 1992. *Rock glaciers and periglacial phenomena in the Southern Carpathians*. Permafrost and Periglacial Processes, 3, 267–273. http://dx.doi.org/10.1002/ppp.3430030317.

Urdea, P., Ardelean, F., Ardelean, M. & Onaca, A., 2022. *Chapter 14-Glacial landscapes of the Romanian Carpathians*. In: Palacios, D., Hughes, P.D., Garcia-Ruiz, J.M. & de Andrés, N. (Eds.) European Glacial Landscapes: *Maximum Extent of Glaciations*. Elsevier, pp. 109–114, https://doi.org/10.1016/B978-0-12-823498-3.00031-5.

Urdea, P., Ardelean, F., Ardelean, M., Onaca, A. & Berzescu, O., 2024. *Chapter 18-Glacial landscape evolution during the Holocene in the Romanian Carpathians.* In: Palacios, D., Hughes, P. D., Jomelli, V. & Tanarro, L. M. (Eds.) *European Glacial Landscapes: The Holocene.* Elsevier, pp. 331-351, https://doi.org/10.1016/B978-0-323-99712-6.00009-X.

Viviroli, D., Kummu, M., Meybeck, M., Kallio, M. & Wada, Y., 2020. *Increasing dependence of lowland populations on mountain water resources.* Nature Sustainability, 3, 917–928, https://doi.org/10.1038/s41893-020-0559-9.

Wagner, T., Pauritsch, M., Mayaud, C., Kellerer-Pirklbauer, A., Thalheim, F. & Winkler, G., 2019. *Controlling factors ofmicroclimate in blocky surface layers of two nearby relict rock glaciers (Niedere Tauern Range, Austria).* Geografiska Annaler: Series A, Physical Geography 101(4), 310-333, https://doi.org/10.1080/04353676.2019.1670950.

Wagner, T., Brodacz, A., Krainer, K. & Winkler, G., 2020. *Active rock glaciers as shallow groundwater reservoirs, Austrian Alps.* Grundwasser - Zeitschrift der Fachsektion Hydrogeologie, 25, 215–230, https://doi.org/10.1007/s00767-020-00455-x.

Wagner, T., Seelig, S., Helfricht, K., Fischer, A., Avian, M., Krainer, K. & Winkler, G., 2021. *Assessment of liquid and solid water storage in rock glaciers versus glacier ice in the Austrian Alps.* Science of The Total Environment, 800, 149593, https://doi.org/10.1016/j.scitotenv.2021.149593.

Williams, M.W., Knauf, M., Caine, M., Liu, F. & Verplanck, P.L., 2006. *Geochemistry andsource waters of rock glacier outflow Colorado Front Range.* Permafrost and Periglacial Processes, 17(1), 13–33, https://doi.org/10.1002/ppp.535.

Received: 13. 04. 2025
Revised: 11. 04. 2025

Accepted: 25. 04. 2025
Published: 25. 04. 2025