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Spring water resources in the Tatra Mountains

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Highlights
- Specific spring runoff in the Polish Tatra Mountains amounts to 12.9 $dm^3 \cdot s^{-1} \cdot km^{-2}$.
- Crenological index for the Polish Tatra Mountains amounts to 4.8 springs·km^{-2}.
- Spatial spring variability depends on tectonic unit, physico-geographic region and altitude.
- Only five largest karst spring contribute to 65% of groundwater resources.

Abstract: The Tatra Mountains stand out as the wettest and most water-rich region in Poland. Despite this, limited studies addressed this issue, and current knowledge largely relies on data obtained in the mid-20th century, with a substantial lack of current estimates. This study aims to fill this gap by evaluating the contemporary water resources of springs in the Tatra Mountains. The study bases on the most recent hydrological mapping of 1,018 springs. The spring resources were evaluated using parameters such as the number of springs, specific runoff, and crenological index, analysed across different physiographic regions, tectonic units, and altitudinal zones. Our studies showed that the highest number of springs occurs in the Western Tatras (66%) between 1000 and 1400 m a.s.l., especially within the Sub-Tatric unit. Springs with discharges ranging from 0.1–1.0 $dm^3 \cdot s^{-1}$ constitute approximately 70% of all springs but they contribute to only 8.1% of spring water resources. Total spring discharge amounted to 2726 $dm^3 \cdot s^{-1}$ and was higher in the Western Tatras (1982.5 $dm^3 \cdot s^{-1}$) than in the High Tatras (743.5 $dm^3 \cdot s^{-1}$). The specific runoff amounted to 12.9 $dm^3 \cdot s^{-1} \cdot km^{-2}$ with the highest total runoff at altitudes occupied by the most abundant karst springs (1000–1100 m a.s.l.). The crenological index amounted to 4.8 springs·km^{-2} and was higher in the Western Tatras (6.5 springs·km^{-2}) than in the High Tatras (4.9 springs·km^{-2}). The analysis revealed that the only five largest karst springs, constituting a mere 0.5% of all springs, account for 65% of spring water resources in the Tatras.

Keywords: crenological index, karst springs, Polish Tatra Mountains, specific runoff, springs

INTRODUCTION

A spring is a natural outflow of groundwater at the Earth's surface, serving as a vital connector between terrestrial and aquatic ecosystems, bridging ground and surface waters, and linking springs to headwater streams (Cantonati *et al.*, 2022). Springs play a crucial role in both ecological and human contexts due to their unique characteristics and the multitude benefits they provide. Springs act as biological hot spots supporting diverse ecosystems (Kurzweil *et al.*, 2021; Work, 2023) and providing various ecosystem services. Moreover, they serve as vital sources of freshwater for drinking, agriculture, and industry in many regions (Adhikari *et al.*, 2021; Niraula *et al.*, 2021). Throughout history, springs have held cultural, spiritual, and historical significance for various human societies (Stevens, Schenk and Springer, 2021) and continue to attract visitors as destination places for recreation and tourism (Kusdibyo, 2022). The distribution and characteristics of springs serve as proof of groundwater resources and circulation patterns in a given geographic area (Mocior *et al.*, 2015; Iván *et al.*, 2020). One of the most important characteristics of every spring is its discharge, which provides insight into the quantity of water within a water-bearing layer or groundwater aquifer and indirectly reflects the physical size of groundwater reservoir (Chełmicki *et al.*, 2011). The discharge of perennial springs helps predict low flows in mountain basins (Cervi *et al.*, 2017). Spring discharge is influenced by a variety of geological (rock types, aquifer characteristics), hydrological (snowmelt dynamics, rainfal-runoff relationships), climatological (precipitation patterns, temperature) environmental (slopes, aspects, elevation, vegetation cover, land use) and anthropogenic factors (Negi and Joshi, 2004; Siwek and Pociask-Karteczka, 2017).

The Polish Tatra Mountains exhibit a complex geological structure, where crystalline igneous rocks neighbour carbonate sedimentary formations, leading to intricate water migration routes. Furthermore, the diverse relief combined with altitudinal zonation of climatic conditions and land cover contribute to great abundance of hydrological phenomena, including the presence of springs. So far, little research has focused on the factors determining the distribution of springs in the mountains, with only a few studies addressing this topic (eg. Grasby and Lepitzki, 2002; Luca de *et al.*, 2015; Mocior *et al.*, 2015; Buczyński, 2018; Martinić and Čanjevac, 2024). The challenges in mountainous regions include the large area, high altitudes, and limited accessibility. From this perspective, the Tatra Mountains cover a small area, have relatively low elevations, and are more accessible compared to other mountain ranges. These factors make it feasible to conduct comprehensive hydrological mapping of springs at all altitude zones, which is a rarity in other mountain ranges.

Hydrological investigation of springs in the Tatra Mountains traces back to the mid-19th century, with first measurements conducted by Zejszner (1844). However, systematic hydrological studies began in 1918 (Ziemońska, 1974). Detailed hydrological mapping of the entire part of the Polish Tatra Mountains was undertaken in the 1950s, leading to the creation of the "Hydrographic map of the Western Tatras" and the "Hydrographic map of the High Tatras" (Wit and Ziemońska, 1960b; Wit-Jóźwik, 1970; Wit-Jóźwik, 1974). In the 1970s, a hydrogeological monitoring network, embracing the Tatra vaucluse springs and major springs, was established in the following studies: Małecka (1996) and Małecka (1997). This was accompanied by detailed inventory of springs, including their discharge as well as physical and chemical characteristics (Małecka, 1996; Barczyk, 2008). Despite the extensive hydrological investigations in the Tatras in the past, more recent comprehensive studies covering the entire region are lacking.

Current knowledge relies primarily on data from the 1950s. Therefore, the objective of this study was to explore the spatial distribution and discharges of springs across the entire Polish Tatra Mountains. Understanding the spatial variability of spring discharge is crucial for effective water resource management, ecological studies, and predicting the effects of climate change and human activities on groundwater resources.

STUDY AREA AND METHODS

STUDY AREA

The Tatras constitutes the highest mountain range in the Carpathians and serve as natural boundary between Poland and Slovakia (Fig. 1). They cover approximately 750 km^2, 20% of which is located in Poland. The Tatras are protected through various means, including national parks, UNESCO transboundary biosphere reserve and Natura 2000.

The Tatras have complex geological structure. The southern part of the mountains, constituting crystalline basement, consists of granitoids in the east and metamorphic rocks in the west (Gawęda *et al.*, 2017). The autochthonous and allochthonous Mesozoic sedimentary rocks of the Upper and Lower Sub-Tatric units, predominantly composed of limestones, dolomites, marls, quartzites, and schists, lie to the north of the crystalline basement (Marks, Grabowski and Stępień, 2022). These formations were folded and displaced northward during the Alpine orogeny. Karst

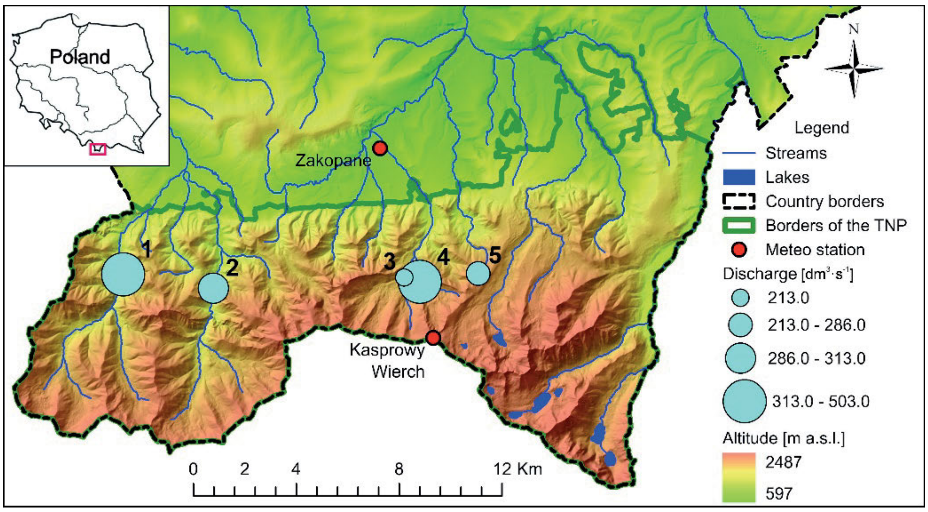

Fig. 1. The study area; source: own elaboration

processes developed in limestones, especially in the High-Tatric Unit. The diverse geology of the Tatras contributes to a variety of habitats and ecosystems, fostering rich biodiversity. Research conducted by Smieja (2014) revealed the occurrence of 239 plant taxa within the spring habitats, varying according to altitude, substrate composition and water pH. Tatra Mountains exhibit typical Alpine relief, primarily shaped by glacial and periglacial processes (Rączkowska, 2021). The Tatra Mountains are characterised by the altitudinal zonation of climate, plant species, soil types, and morphogenetic processes (Mirek, 2013; Łupikasza and Szypuła, 2018). The average precipitation totals in the Polish Tatra Mountains varies between 800 mm at the foot of the mountains to 1,800 mm on the mountain peaks, while the average annual air temperature is 6–7°C and 0°C, respectively (Bokwa *et al.*, 2021).

Groundwaters in the Tatra Mountains are separated from the surface by an aeration zone, enabling springs to respond quickly to atmospheric precipitation. However, they are also highly vulnerable to human pressure (Małecka *et al.*, 2002). Two types of groundwater occur in the Tatras: shallow circulation, which follows the slope of the terrain, and deep circulation, influenced by lithological and structural units as well as the course of dislocations (Małecka, 1993). Mesozoic and Eocene carbonate formations constitute the major water-bearing aquifers in the Tatras. These formations are highly fractured and karstified, with a fracture coefficient of 7% (i.e., ratio of the number of fractures in a given area to its surface area) (Chowaniec, 2009). Relatively small aquifers are formed within glacial moraines and fluvioglacial formations. The crystalline basement has low water permeability, extending only to a depth of 20–30 m. Therefore, the springs occurring in this area have no functional significance (Chowaniec, 2009). The Tatra Massif plays a crucial role in shaping hydrological conditions of the entire Podhale region. It serves as primary recharge area for surface and sub-surface waters, as well as for the sub-flysch aquifers (thermal) of the Podhale artesian basin (Małecki, 1997).

METHODS

Hydrological mapping of springs was carried out twice in the years 2007–2009, during which 1,018 groundwater outflows were inventoried such as seepage springs (i.e., tricking of groundwater without visible surface outflow), leakage springs (i.e., ground water leakage with visible surface outflow), fracture springs (i.e., concentrated outflow from faults, joints, and fissures in low permeability rocks), karst springs (i.e., outflow of groundwater from carbonate rocks), vaucluse springs (i.e., high-yield karst springs with discharge over 100 $dm^3 \cdot s^{-1}$), and seepage spring areas (Alfaro and Wallace, 1994). Spring discharge was measured using the volumetric method. Only the discharge of large springs and vaucluse springs was measured with instrumental methods, using an electromagnetic current flow meter Valeport-801. Springs with visible outflow but very weak discharges were classified as springs having a discharge below 1 $dm^3 \cdot s^{-1}$. Field measurements were conducted during the summer-autumn low flow period when the hydration of the mountains was low, starting from the last week of August until mid-September.

At the time of mapping, the average annual precipitation totals closely matched the average rainfall totals from the 1956–2006 period, amounting to approximately 1,600 mm on Kasprowy Wierch and 1,100 mm in Zakopane. Monthly rainfall totals in August and September, both in Zakopane and on Kasprowy Wierch, were lower than the average for the 1961–2000 period.

For the purpose of the study, various parameters were calculated, including the number of springs, density of springs (crenological index), specific runoff and water resources representing the total outflow of all springs. The calculations were performed for the entire area of the Polish Tatra Mountains, as well as for physio-geographical regions (Western and High Tatras), tectonic units (High-Tatric unit, Lower Sub-Tatric unit, Upper Sub-Tatric unit) and elevation zones with 100 m contour interval. Statistically significant differences in discharge of springs between physio-geographical regions, tectonic units, and elevation zones were tested at $p = 0.05$ significance level using ANOVA and Scheffe's post hoc test, correspondingly. For simplicity, the border of the Tatra National Park was considered as the area of the Polish Tatra Mountains.

RESULTS AND DISCUSSION

THE ABUNDANCE AND DENSITY OF SPRINGS

A total of 1,018 springs were mapped in the Polish Tatras, with 66% located in the Western Tatras and the remaining 34% in the High Tatras. Approximately 52% of these springs occurs within carbonate sediments of the Tatra Mountains, while the remaining 48% are situated within the crystalline basement. However, the distribution of springs within the carbonate rocks is uneven. The majority of springs is concentrated in the karst area of the Sub-Tatric units. Only a few springs were found in the karst area of the High-Tatric units, constituting only 11.5% of all springs in the Tatras (Tab. 1). During the mapping conducted in the 1960s and 1970s, a total of 1,154 groundwater outflows were identified, with 52% in the Western Tatras and the remaining 48% in the High Tatras. At that time, springs located in the crystalline basement of the Tatras were predominant, while a lower number of springs were found in the High-Tatric units (Wit and Ziemońska, 1960a; Wit-Jóźwik, 1974).

Table 1. The abundance of springs in the Tatras in relation to geological units and physico-geographical regions

Specification	Study period	
	2007–2009	1960s, 1970s
Tectonic unit (percentage)		
Crystalline basement	48.0	62.0
High-Tatric units	11.5	4.0
Sub-Tatric units	40.5	34.0
Physico-geographical region (number of objects)		
High Tatras	350	551
Western Tatras	668	603
Tatra	**1018**	**1154**

Source: own study, Wit and Ziemońska (1960b), Wit-Jóźwik (1974), and Łajczak (1996).

The crenological index of the Polish Tatra Mountains accounts to 4.8 springs·km^{-2}. The obtained density of springs in the Tatras is lower than values reported during previous studies conducted in the 1960s, 1970s and 1980s. By comparison, the average crenological index obtained by Ziemońska (1973) was approximately 7.0 springs·km^{-2}. In turn, spring densities reported by Kostrakiewicz (1996) and Małecka (1997) were 6.0 and 5.5 springs·km^{-2}, respectively.

In the Western Tatras, the crenological index reaches 6.5 springs·km^{-2}, whereas in the High Tatras, it stands at 4.9 springs·km^{-2} (Tab. 2). During the 1960s and 1970s, the density of springs in the Western Tatras was slightly lower, amounting to 5.3 springs·km^{-2} (Wit and Ziemońska, 1960a), while in the High Tatras, it was slightly higher with 7.5 springs·km^{-2} (Wit-Jóźwik, 1974). These discrepancies are associated with variations in hydrometeorological conditions during hydrological mapping. The High Tatras were mapped during a wetter period (approximately 10% higher annual rainfall), while the Western Tatras were mapped during lower rainfall totals. The research revealed variations in the crenological index closely linked to the geological and tectonic structure of the Tatra Mountains. Higher values of crenological index, reaching 6.8 springs·km^{-2}, are observed in the crystalline basement of the Tatras, whereas lower values are found within the carbonate sediments, particularly in the karst area of the High-Tatric units.

Similar regularities were observed in studies conducted in the 1960s, 1970s and 1980s, however the values obtained in the previous studies differ significantly (Tab. 2). High number of springs in the crystalline basement of the Tatras is associated with hydrological, meteorological, and geological conditions. The area is characterised by exceptionally high rainfall totals and prolonged snow cover, which can persist locally throughout the year. The crystalline basement of the Tatras is dominated by fissure springs, formed in the cracked zone of rocky slopes, as well as the seepage springs, emerging from local water reservoirs formed within thick moraine deposits and talus cones (Łajczak, 1996; Łajczak, 2006). The pronounced fragmentation of terrain and low porosity of rocks result in a higher number of low discharge outflows. A notably lower spring densities in the High-Tatric units are linked to extensive fractured karst systems within dolomites and limestones of the Middle Triassic, as evidenced by a substantial number of caves (805) (Gradziński *et al.*, 2009). This indicates a scarcity of surface waters in the High-Tatric unit and mountain slopes. Instead, there is a prevalence of long-term and deep groundwater flows, which emerge to the surface in the form of high discharge vaucluse springs at the contact zones between karst rocks and poorly or impermeable formations (Łajczak, 1996; Barczyk, Humnicki and Żurawska, 2002).

Table 2. Crenological index (obj. per km^2) in the Tatras in relation to geological units and physicogeographical regions

Specification	Index in the study period	
	2007–2009	1960s, 1970s, 1980s
Tectonic unit		
Crystalline basement	6.8	6.5–16.0
High-Tatric units	3.5	1.0–3.5
Sub-Tatric units	5.9	4.0–12.0
Physico-geographical region		
High Tatras	4.9	7.5
Western Tatras	6.5	5.3
Tatra	**4.8**	**7.0**

Source: own study, Wit and Ziemońska (1960b), Wit-Jóźwik (1974), Ziemońska (1973), Małecka (1997), Kostrakiewicz (1996), and Łajczak (1996).

GROUNDWATER RESOURCES

During the mapping conducted between 2007 and 2009, the total discharge of all springs in the Polish Tatra Mountains amounted to 2726 dm^3·s^{-1} (Tab. 3). Groundwater resources, expressed as specific runoff, reached 12.9 dm^3·s^{-1}·km^{-2}, equivalent to a 406 mm water layer. Total spring discharge amounted to 1982.5 dm^3·s^{-1} in the Western Tatras and 743.5 dm^3·s^{-1} in the High Tatras. For comparison, spring water resources obtained during mapping in the 1960s and 1970s were nearly double, amounting to 5279 dm^3·s^{-1} (approx. 4000 dm^3·s^{-1} in the Western Tatras and about 1280 dm^3·s^{-1} in the High Tatras), corresponding to a specific runoff of 28.4 dm^3·s^{-1}·km^{-2} (Wit and Ziemońska, 1960a; Wit-Jóźwik, 1974). This discrepancy is attributed to different hydrological and meteorological conditions during the mapping periods, rather than an actual decline in regional water resources (Żelazny *et al.*, 2021). Notably, the obtained specific runoff from the Tatra Mountains aligns closely with those (11.8 dm^3·s^{-1}·km^{-2}) reported by Małecka, Chowaniec and Małecki (2007), who also emphasised substantial variation in runoff across the Tatras, ranging from 2 to over 25 dm^3·s^{-1}·km^{-2}. In turn, the average specific runoff obtained by Wolanin and Pęksa (2012), during exceptionally severe winter low flow at the turn of 2011 and 2012, amounted to 7.25 dm^3·s^{-1}·km^{-2}.

Based on discharge, six classes of springs were distinguished in the Tatra Mountains according to Meinzer's (1923) classification adapted to metric system (Alfaro and Wallace, 1994). Springs with discharges ranging from 0.1–1.0 dm^3·s^{-1}, belonging to the 6th Meinzer class, constitute approximately 70% of all springs. Despite their abundance, they contribute to only 8.1% of spring water resources in the Tatras. Only five springs belong to the highest 3rd discharge class (100–1000 dm^3·s^{-1}) – Table 3. These

Table 3. Number of springs and estimated groundwater resources in the Tatras

Meinzer's class	Spring water resources		Springs	
	total runoff (dm^3·s^{-1})	%	number	%
3	1760.0	64.6	5	0.5
4	321.5	11.8	10	1.0
5	416.9	15.3	157	15.4
6	220.7	8.1	705	69.3
7	6.8	0.3	139	13.7
8	0.01	0.0004	2	0.2
Total	**2725.9**	**100.0**	**1018**	**100.0**

Source: own study.

are: Bystra (3), Chochołowskie (1), Goryczkowe (4), Lodowe (2) and Olczyskie (5) vaucluse springs (Fig. 1), constituting a mere 0.5% of all springs, yet they account for the largest share of groundwater resources. Together, they supply 1760 $dm^3 \cdot s^{-1}$ of water, representing 64.6% of the entire groundwater resources of the Tatras. High discharges of these springs are associated with extensive deep-water drainage of karst aquifers formed within the High-Tatric units. In turn, high discharges of the Olczyskie and Goryczkowe vaucluse springs are attributed to large alimentation areas that extend beyond the topographic boundaries of catchments, reaching into the crystalline basement of Tatras (Barczyk, Humnicki and Żurawska, 2002; Gromadzka *et al.*, 2015). The recharge areas may be up to twice as large as the catchment area. Additionally, research conducted in other karst basins in high-altitude regions has indicated a decrease in recharge areas with increasing average recharge elevations (Iacurto *et al.*, 2021). Previous research on springs in various regions of Poland indicated that fissure springs, despite being more numerous and having lesser yield, display high variability of discharge. However, the highest variability is observed in high mountain karst springs, which experience a broad range of discharge extremes due to abundant summer precipitation and limited winter recharge (Bartnik and Moniewski, 2019). Our results showed that Podhale displays the highest variability in spring discharges, while the Western Tatra exhibits the lowest variability (Fig. 2). However, the differences in discharge variability among the regions are not statistically significant (F = 2.13; p = 0.119). From a geological perspective, the High-Tatric unit exhibits the greatest variability in spring discharges, whereas the Sub-Tatric unit shows the least variability. The Podhale and crystalline units demonstrate moderate variability. The median discharge values are relatively low across geological units, with the High-Tatric unit having the highest median discharge, though it is still relatively small compared to its range of variability (Fig. 2). The differences in the variability of spring discharge among the geological units are statistically significant (F= 22.97; p = 0.00).

THE VARIABILITY OF GROUNDWATER RESOURCES IN DIFFERENT ELEVATION ZONES

Springs in the Tatra Mountains are found at altitudes ranging from 800 up to 2,000 m a.s.l. There is a noticeable increase in the number of springs from the foot of the mountains up to an altitude of 1,100 m a.s.l. Beyond this altitude, the number of springs generally decreases with increasing altitude (Fig. 3). The majority of springs is concentrated between 1,000 and 1,400 m a.s.l. The abundance of springs in this elevation range is associated with streams cutting down to the level of karst water aquifers and the presence of moraine water aquifers. The scarcity of springs in the highest parts of the Tatra Mountains is in turn associated with the limited infiltration and storage. Steep slopes, combined with limited cracks in the bedrock and low permeability of covers create unfavourable conditions for the occurrence of springs. The highest total runoff is observed in the altitudes occupied by the most abundant karst springs in the Tatra Mountains such as the Olczyskie vaucluse spring lying between 1,000 and 1,100 m a.s.l. and the Bystra and Goryczkowe vauculse springs situated between 1,100 and 1,200 m a.s.l. (Barczyk, Humnicki and Żurawska, 2002). Additionally, a significant number of moraine springs with high discharges are found between 1,300 and 1,400 m a.s.l. in the crystalline part of the Tatras. This distribution is primarily associated with hydrogeological conditions and land relief, which is a regularity rather often observed in high-mountain areas with mixed geological structure (eg. Iván *et al.*, 2020; Martinić and Čanjevac, 2024). The altitude range of 1,400–1,450 m exhibits the highest variability in spring discharges, while several altitude ranges (e.g., 900–950 m, 1,050–1,100 m, 1,300–1,350 m) display relatively low variability. The ANOVA results suggest that differences in the variability of spring discharges between altitude zones are statistically significant; however, the Scheffe's test did not confirm this regularity. The zone of glacial moraines in the crystalline part of the Tatras is characterised by gentle slopes and thick layers of easily permeable sediments overlying the impermeable rock.

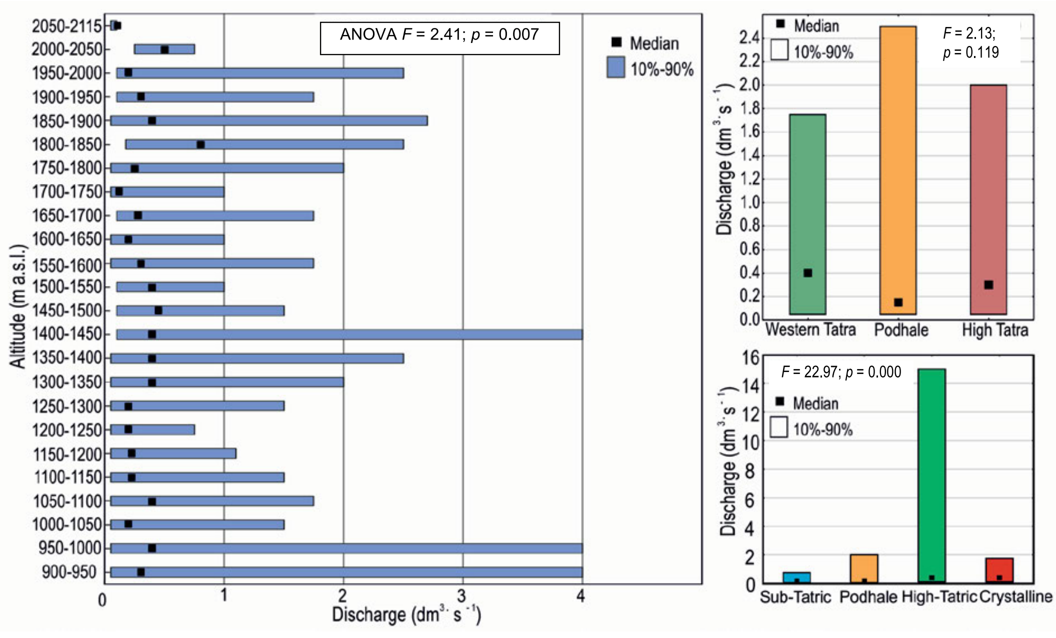

Fig. 2. Distribution of spring discharge in elevation zones and hydrogeological regions; source: own study

Moraine deposits fill depressions in terrain, such as valleys and glacial cirques, facilitating the storage of significant water volumes. Approximately 90% of groundwater resources in the crystalline part are stored in moraine reservoirs (Łajczak, 1996), leading to a notably high specific runoff (approximately 40 $dm^3 \cdot s^{-1} \cdot km^{-2}$), particularly between 1,300 and 1,400 m a.s.l. However, the highest specific runoff is observed between 900 and 1,000 m a.s.l., reaching nearly 150 $dm^3 \cdot s^{-1} \cdot km^{-2}$. It is worth noting that this runoff originates solely from springs emerging from the Sub-Tatric units. High-altitudes between 1,000 and 1,100 m a.s.l. stand out in terms of spring density, with the highest crenological index amounting to 210 springs per square kilometer. Nearly all springs in this altitudinal range are situated within the High-Tatric units.

CONCLUSIONS

The specific runoff of spring in the Tatra Mountains ranks among the highest in Poland, reaching 12.9 $dm^3 \cdot s^{-1} \cdot km^{-2}$. The crenological index for the entire Polish Tatra Mountains amounts to 4.8 $springs \cdot km^{-2}$. Spatial variability of springs is evident across physical and geographical zones, main geological and tectonic units, particularly pronounced in high-altitude regions, where the index may exceed 200 springs per square kilometer. The spatial distribution of springs clearly refers to the hydrogeological conditions of the region and, which is a common regularity in high-mountain areas with mixed geological structure. The majority of springs is concentrated between 1,000 and 1,400 m a.s.l. The High-Tatric unit exhibits the highest variability in spring discharges, whereas the Sub-Tatric the lowest. Springs with discharges ranging from 0.1–1.0 $dm^3 \cdot s^{-1}$, belonging to the 6th Meinzer class, constitute approximately 70% of all springs. Despite the fact that low discharge springs prevail in the Tatras, only five largest karst spring contribute to 65% of groundwater resources.

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CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

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