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Springs as Natural Sensors for Sustainable Groundwater Monitoring: Bridging Hydrodynamics, Telemetry and System Constraints

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Abstract

Groundwater is a key strategic resource underpinning water security, and its effective management requires reliable, high-frequency monitoring data. In mountainous regions such as the flysch Carpathians in southern Poland, natural springs are particularly sensitive indicators of aquifer system dynamics. This study analyzes the role of springs in the national groundwater observation and research network and identifies barriers to the implementation of automated monitoring of spring discharge. The research covered 28 springs operating within the regional monitoring network of the Polish Geological Institute – National Research Institute in the Carpathian region. Classical hydrogeological spring classifications were applied and complemented with proprietary criteria addressing formal-legal, technical, and environmental conditions affecting the feasibility of automation. The results show that most analyzed springs exhibit high discharge variability and rapid responses to precipitation, indicating that weekly manual measurements are insufficient to capture flow dynamics. The main barriers to telemetry implementation are non-technological and related primarily to ownership, administrative, and environmental constraints. The proposed spring classification framework supports rational planning of monitoring network automation and may be applicable in other mountainous regions with similar hydrogeological conditions.

Keywords: groundwater monitoring; spring discharge; automated monitoring; telemetry systems; flysch aquifers; Carpathian springs; water resource management

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1. Introduction

Groundwater constitutes a strategic freshwater resource upon which the water security of more than half of the global population depends [1]. In the era of climate instability and increasing anthropogenic pressure on water resources, groundwater has attracted growing attention in the field of water resources management due to its crucial role in sustaining water supply systems and ecosystems [2,3]. Recent studies highlight that climate change significantly affects groundwater recharge processes, evapotranspiration patterns, and hydrological extremes, thereby increasing uncertainty in the availability and long-term sustainability of groundwater resources [4–6].

In Central Europe, including Poland, the increasing frequency of extreme weather events—from rapid floods to prolonged droughts—poses new challenges for water resource management systems [7,8]. Across most of Europe, the structure of precipitation has changed, with a significant increase in the number of days characterized by high-intensity rainfall [9,10]. However, these changes do not alter the fact that Poland is still classified as a country with relatively limited water resources. Therefore, rational management and sustainable use of groundwater resources are of key importance, as groundwater constitutes a stable source of drinking water supply and water available for agriculture, significantly more resilient to climate variability and extreme events than surface water resources. Moreover, under the hydroclimatic conditions of Central Europe, groundwater is generally characterized by higher physicochemical quality compared with surface waters [11]. In contrast, under the semi-arid climatic conditions of the Iberian Peninsula, the opposite relationships are often observed [12]. Although surface water dominates in the overall water balance, groundwater resources supply more than 70% of drinking and domestic water demand in Poland [13], highlighting their strategic importance for national water security.

Famiglietti [14] emphasizes that groundwater depletion may pose a much greater threat to water security than is commonly assumed, which necessitates a transition from traditional management approaches toward modern monitoring systems capable of reducing high levels of data uncertainty. In recent years, increasing attention has been paid to the development of advanced monitoring networks and integrated observation systems enabling continuous assessment of groundwater dynamics and more effective resource management [15–17]. On a global scale, groundwater monitoring networks operate in most countries across all continents, not only in Europe but also, for example, in Korea [18], Egypt [19], New Zealand [20], the United States [21], Brazil [22], and South Africa [23]. However, these networks show considerable variability in terms of monitoring point density, measurement accuracy, and the level of institutional supervision. Despite these differences, their efficient functioning is of critical importance because groundwater constitutes a key strategic reserve that allows societies to withstand periods of precipitation deficit and hydrological drought. Without systematic monitoring and sustainable management of these resources, global water security may be threatened to a much greater extent than is currently widely recognized [14].

In Poland, a stationary groundwater observation network was established as early as 1969 [24]. The Polish observation and research network is characterized by a long tradition and a multi-level institutional structure. The monitoring network currently includes various types of observation points, such as drilled hydrogeological wells (including monitoring wells and piezometers), dug wells - gradually being phased out and replaced by drilled wells - as well as natural springs. However, long-term experience with the monitoring network indicates that traditional methods for measuring spring discharge based on periodic manual readings are insufficient in regions characterized by highly dynamic hydrogeological conditions, such as the Carpathian Mountains. Mountainous areas dominated by fractured aquifers and complex hydrogeological systems typically exhibit very rapid responses to precipitation infiltration. Consequently, conventional monitoring approaches with low temporal resolution may fail to capture short-term fluctuations in spring discharge and groundwater levels [25,26]. Recent studies emphasize that high-frequency automated spring monitoring significantly improves the understanding of groundwater recharge processes, hydrological variability, and the early detection of hydrological extremes [27].

According to the authors of this study, the implementation of automated monitoring systems enabling high-frequency measurements of spring discharge is essential for accurate drought forecasting and for protecting groundwater resources from overexploitation and degradation. Only reliable and systematically collected measurement data enable effective management of water resources under conditions of increasing climatic variability and growing anthropogenic pressure [6,14,28]. Continuous monitoring of groundwater levels and groundwater abstraction is also fundamental for the effective management of groundwater resources, particularly in transboundary basins where the lack of reliable and comparable data may hinder rational water management and international cooperation. Furthermore, well-functioning monitoring networks allow early detection of groundwater overexploitation, which may lead to irreversible depletion of aquifer resources, land desiccation, and degradation of groundwater-dependent ecosystems such as springs and wetlands.

2. Materials and Methods

2.1. Structure and Short History of Groundwater Monitoring Network

The origins of groundwater monitoring in Poland, carried out by the Polish Geological Institute – National Research Institute (PIG-PIB), date back to the late 1950s and early 1960s. The basic observation network was officially established in 1972, with its main objective being to monitor natural fluctuations in water levels and to protect resources from overexploitation and degradation. It is worth noting that as early as the 1990s, testing of continuous, automatic measurement recording began at selected hydrogeological stations (boreholes), which was a pioneering solution in relation to modern telemetry.

The factor that necessitated a major reorganisation of the network was Poland’s accession to the European Union in 2004 and the need to implement the Water Framework Directive 2000/60/EC (WFD), both in the management of surface waters [29] and the groundwater bodies (GWBs) in question. In 2006, the previously separate quantitative and qualitative networks were merged into a single observation and research network. The assessment of the status of GWBs became a priority, which required a significant increase in the density of monitoring points.

The current structure of the network comprises nearly 2,000 monitoring points, divided into quantitative status monitoring, qualitative (chemical) status monitoring and research monitoring. In the Polish groundwater monitoring system, observation and research points are classified according to their rank and the scope of the research carried out; the most important role is played by first-order hydrogeological stations, whose design and equipment allow for a full range of observations to be carried out across all exploitable aquifers present in a given region. Second-order points consist of wells, piezometers and cased springs, which play a supplementary role and are used mainly for regular measurements of the water table or yield, as well as for taking samples for physico-chemical analysis.

2.1.1. Quantitative Monitoring

Quantitative monitoring in Poland is based on just under 1,200 stations in the hydrogeological observation system (Figure 1).

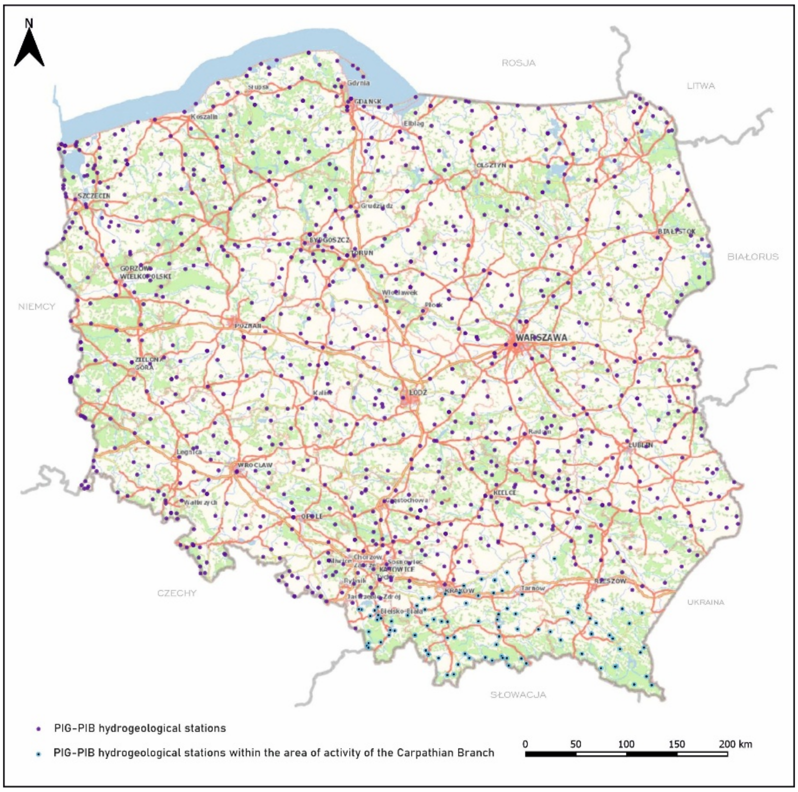

Figure 1. Locations of hydrogeological stations the PIG-PIB National Groundwater Observation and Research Network.

The monitoring process is based on regular measurements of the water table depth and spring discharge, which allows for tracking natural variability and the effects of human pressure [30]. The collected data is used to balance available resources and assess their utilization, as well as to forecast threats such as hydrogeological droughts. Since 2013, the system has been gradually modernized through the implementation of equipment for automatic measurement and data transmission, which increases the effectiveness of crisis management and reporting to the European Commission. In 2019, telemetry systems were already operational at 366 locations, transmitting data on water level and temperature to the servers of the State Hydrogeological Service.

It is extremely important to note that the use of telemetry in quantitative groundwater measurements described above applies exclusively to hydrogeological boreholes, i.e., drilled wells and piezometers. To date, natural springs serving as active observation and research points in Poland’s groundwater network have not been equipped with devices capable of continuously recording variations in discharge. This therefore poses a challenge for the organizers of the national groundwater observation and research network in Poland.

2.1.2. Quality Monitoring

The monitoring of groundwater chemical status in Poland, which has been conducted continuously since 1991, serves as a fundamental tool for protecting water quality and detecting pollution at an early stage. In accordance with EU (WFD) and national requirements [31], chemical monitoring is divided into three main types: diagnostic, operational, and research. Diagnostic monitoring is used for a comprehensive assessment of the chemical status of all GWBs and is conducted at least once every six years, while operational monitoring focuses on areas at risk of degradation or already identified as being in poor condition, requiring more frequent measurements (usually twice a year) to track trends [30,32].

2.1.3. Research Monitoring

Supplementary monitoring is conducted in cases of incidental pollution or to determine the reasons for failing to meet environmental targets [32]. The results obtained, covering a wide range of physicochemical parameters and organic substances, are compiled in an integrated database and form the basis for preparing annual reports and bulletins on the country’s hydrogeological situation.

An important element of the national groundwater observation and research network is research monitoring covering border areas (in accordance with international agreements) and regions subject to high anthropogenic pressure, such as urban agglomerations and mining areas. The primary objective of research monitoring of border areas is to assess the impact of groundwater exploitation on both sides of national borders on their resources and chemical composition, which allows for the collection of reliable data on transboundary aquifers. Currently, research monitoring covers border zones with all neighbors, with the exception of Russia.

The current monitoring network is no longer merely a documentation tool, but an active decision-support system that, thanks to automation, allows for the assessment of changes in groundwater resources in near real time.

Because Poland’s groundwater monitoring network has undergone a thorough evolution to align with European standards, it has become compatible with the systems of other EU countries, enabling data reporting to the European Environment Agency. Monitoring data is used in international reporting, which places the Polish system on par with the most advanced observation networks in Europe in terms of monitoring density and the range of physicochemical parameters studied [30]. Within the European context, Poland’s groundwater monitoring network shows the greatest structural, density and geological similarity to the systems in operation in the Czech Republic and Slovakia. This similarity stems from the fact that these countries, like Poland, base their

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monitoring on the principle of representativeness for GWBs within river basins, maintaining a similar density of the core network. Particularly in the Carpathian belt, the Polish spring monitoring network is almost identical in character to the Slovak network, where highly dynamic hydrogeological fractured aquifers of the Carpathian flysch dominate. This fact determines the necessity of monitoring natural groundwater discharges, i.e., springs, as key indicators of the state of water retention [33]. Springs form the core of this publication

2.2. Reference Area in Groundwater Monitoring Network

The study area covers the Outer Carpathians in southern Poland. Groundwater in this region is characterized by unique features resulting from its geological structure and topography. The geological structure is dominated by the Carpathian flysch (rhythmically alternating layers of sandstone, mudstone and clay shale), which, as a result of orogenic processes, have been strongly folded and thrust upon one another in the form of nappes. This specific structure determines the hydrogeological conditions of the entire region, which is additionally rich in geothermal waters [34]. There are geothermal springs in the study area, which present certain difficulties in terms of sampling [35]; nevertheless, they are not included in the national monitoring network. Sandstones typically act as aquifers, whilst impermeable shales form isolating barriers. In the western part of the study area, coarse-grained sandstones dominate, whereas towards the east the flysch becomes more diverse, which directly influences the circulation of groundwater. The hydrogeodynamic properties of the Carpathian region are characterized by high dynamics, manifested in a very rapid response of the water table and spring yields to precipitation.

The groundwater monitoring network in the Carpathian region is operated by the Carpathian Branch of the PIG-PIB and is integrated into the national observation and research network. The network comprises 103 observation and research points, 28 of which are springs (Figure 2).

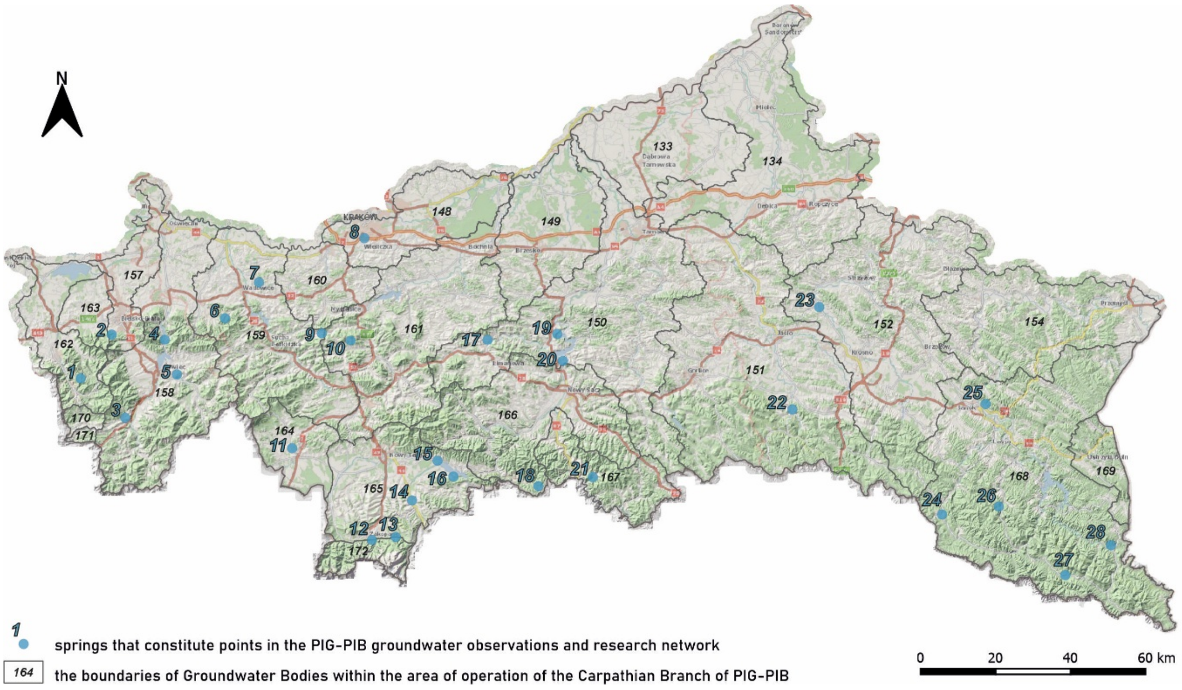

Figure 2. Springs serving as monitoring hydrogeological stations within the operational area of the Carpathian Branch of PIG-PIB (details of the points shown in Table 1).

Table 1. Descriptive statistics of the springs discharge under study.

Spring no. per Figure 2	Name	Min [dm³/s]	Max [dm³/s]	Mean [dm³/s]	Median [dm³/s]	SD	CV%
1	Ustroń-Dobka	0,03	12,82	0,75	0,50	0,93	123,65

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2	Szyndzielnia	0,00	5,41	0,22	0,11	0,37	170,26
3	Kamesznica	0,02	10,00	1,33	0,91	1,36	102,58
4	Czernichów	0,01	7,69	0,49	0,33	0,60	122,21
5	Żywiec-Koleby	0,00	4,50	0,17	0,08	0,30	178,14
6	Ponikiew	0,00	2,63	0,12	0,06	0,21	171,79
7	Babica	0,09	0,96	0,29	0,28	0,09	32,55
8	Kraków-Kurdwanów	0,06	2,63	0,96	0,87	0,48	49,99
9	Bieńkówka	0,00	1,56	0,26	0,18	0,25	95,36
10	Zawadka-Tokarnia	0,01	5,00	0,22	0,13	0,35	163,81
11	Zubrzyca Dolna	0,03	0,15	0,07	0,06	0,02	28,88
12	Zakopane-Capki	0,00	284,15	111,89	150,66	77,50	69,26
13	Koziarczyska	21,62	426,46	137,16	134,80	44,92	32,75
14	Białka Tatrzańska	0,11	1,05	0,24	0,23	0,08	33,28
15	Dębno	0,00	126,18	10,86	9,80	7,14	65,79
16	Falsztyn	0,05	3,43	1,00	0,83	0,67	66,35
17	Młynne	0,02	5,00	0,35	0,27	0,33	92,89
18	Jaworki-Biała Woda	0,00	0,87	0,10	0,08	0,09	87,42
19	Rożnów	0,02	0,25	0,09	0,08	0,04	41,17
20	Zbyszyce-Kurów	0,01	1,00	0,24	0,23	0,12	50,38
21	Wierchomla	0,10	4,50	0,66	0,67	0,34	51,60
22	Kąty	0,01	0,17	0,08	0,08	0,03	38,68
23	Widacz	0,03	0,35	0,10	0,08	0,06	63,21
24	Radoszyce	0,00	2,52	0,63	0,45	0,59	94,73
25	Sanok-Olchowce	0,06	1,25	0,19	0,15	0,13	65,45
26	Bystre-Rabe	0,35	4,42	0,92	0,84	0,38	41,18
27	Wetlina	0,01	2,00	0,23	0,19	0,18	77,71
28	Dwerniczek	0,05	10,20	0,38	0,30	0,44	115,56

Springs in the Carpathians are the most common and natural manifestation of groundwater discharge. In contrast to lowland areas, the Carpathians exhibit an exceptionally high density of springs, which locally exceeds 10 sites per km². This is undoubtedly a feature that sets the Carpathian network apart from the rest of the country, as monitoring elsewhere relies almost exclusively on boreholes. Currently, springs account for as much as 27% of all observation and research points within the Carpathian regional network, reflecting their importance in groundwater circulation in mountainous areas. The Carpathians are the only region in the country where springs play such a significant role in the monitoring system. The sites with the longest measurement series, spanning 38 years, are the publicly accessible flysch springs of Żywiec-Koleby and Babica (Table 1, Table 8). The site that was most recently incorporated into the Carpathian regional observation and research network is the Tatra spring at Koziarczyska. It has been monitored for 8 years.

The use of springs—as spontaneous, natural and concentrated outflows of groundwater to the surface, representing a direct manifestation of the natural drainage of aquifers—is an effective and economically viable alternative to costly drilling work carried out as part of monitoring surveys. From a research perspective, the contribution of springs to the Polish observation and research network is significant; however, the potential of springs appears to remain untapped.

2.3. Measurements Methods

Quantitative groundwater monitoring in Poland focuses primarily on determining the location of the water table and the yield of natural springs. At first-order hydrogeological stations, these measurements are carried out daily (at 06:00 UTC), whilst at second-order stations they are carried out once a week, on Mondays (also at 06:00 UTC). Manual measurements are carried out by trained field observers. In the case of groundwater springs, the methodology for measuring discharge is selected on a case-by-case basis, taking into account the morphology of the outflow and the existing infrastructure. For captured springs, the volumetric method (Figure 3a) or the measuring weir method is most commonly used. At only one point in the Carpathian observation and research network in question, namely at the Koziarczyska spring in the Tatra Mountains, the hydrometric wheel method is used to measure yield (Figure 3b). The selection of the appropriate measurement method is of particular importance in the flysch Carpathians region, where the monitoring of natural groundwater discharges forms the basis for understanding water dynamics in complex fissured systems. The reliability of the data obtained is a prerequisite for maintaining the continuity and comparability of long-term yield data series.

(**a**) (**b**)

Figure 3. Measuring discharge of a spring using (a) the volumetric method (b) hydrometric wheel method.

The rules for recording monitoring data are based on the central groundwater monitoring database, which collects quantitative measurement results (dating back to 1966) and chemical composition data. Data from manual measurements are entered into the database system, whilst for hydrogeological boreholes equipped with automatic instruments (e.g., pressure sensors/loggers), data are transmitted via telemetry. For the purposes of early warning against hazards such as hydrogeological drought, a special data collection procedure has been introduced, enabling the database to be updated more quickly with results from the previous month. Unfortunately, no automated measurement systems have yet been implemented for the springs forming part of the monitoring network.

All collected data are verified and published once a year, presenting statistical summaries and an assessment of the hydrogeological situation for the given hydrological year. This information is made publicly available via dedicated government web applications [36,37].

2.4. The Aim of the Research

Despite the importance of springs in water resource management, traditional manual methods of measuring spring discharge—based on weekly readings—have critical limitations when it comes to accurately capturing the dynamics of groundwater discharge. Infrequent measurement intervals make it impossible to capture the rapid response of springs to rainfall (so-called peak flows) and to accurately determine drawdown curves, leading to a significant underestimation or misinterpretation of dynamic resources, particularly in areas with high porosity [38–40]. A similar issue applies to aquifers with complex hydrodynamics around the world, e.g., spatial-temporal behavior of precipitation driven karst spring discharge in a mountain terrain [41–44]. In the Carpathian flysch region, where aquifer systems are characterized by an exceptionally short response time to infiltration, automated systems capable of continuously recording the full range of flow variations have yet to be implemented. This article attempts to highlight this significant gap in the Polish observation and research network, whilst other European countries have developed, automated spring monitoring systems with high measurement frequencies, often every 15 minutes. In this study, for the first time in the published literature, the problematic nature of implementing automatic spring discharge measurements has been clearly identified and analyzed, in a framework that goes beyond technological issues to include organizational, legal and technical barriers.

3. Results

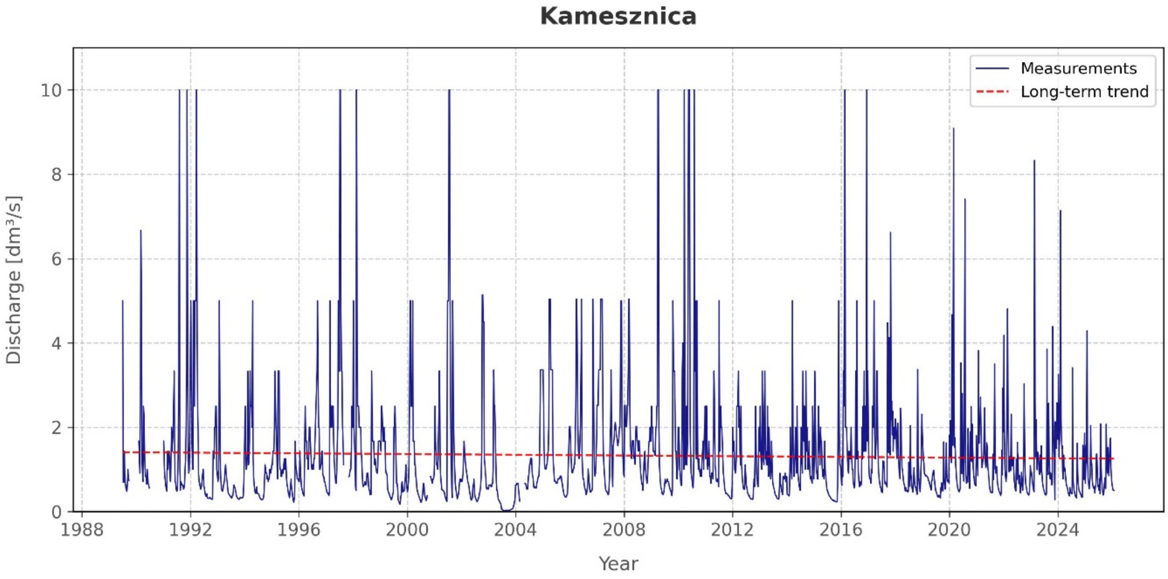
3.1. Spring Discharge Within the Monitoring Network

Basic statistical analysis of the discharge of the 28 monitored springs (Table 1) reveals a significant diversification of hydrogeological conditions in the study area. The vast majority of the objects in the network are characterized by relatively low yields. For 23 springs, the mean discharge does not exceed the value of 1.0. However, the drainage system also includes structures with very high potential, among which the Koziarczyska (No. 13) and Zakopane-Capki (No. 12) springs distinctly stand out. Their mean discharges are 137.16 and 111.89, respectively, while the maximum recorded flows reach values in the range of several hundred units. In the case of objects with such a high amplitude of fluctuations, it was observed that the median, rather than the arithmetic mean, constitutes a much more reliable indicator of the typical recharge state, as it effectively eliminates the impact of short-term, extreme high-flow events on the overall picture of the spring regime.

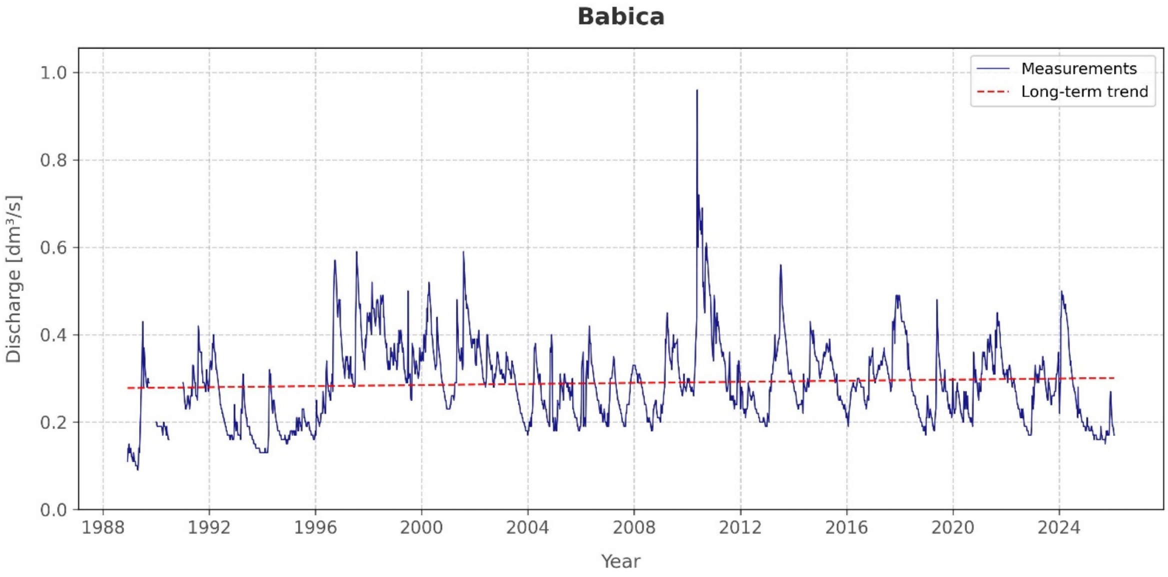
Parameter for assessing the dynamics of aquifer systems is the coefficient of variation (CV%), which allowed for the classification of the studied objects in terms of the stability of their regime. As many as seven of the monitored springs exhibit extremely high variability (CV > 100%, e.g., Żywiec-Koleby—178.14%, Ponikiew—171.79%), which, indicates these springs are recharged from shallow groundwater circulation systems, making them respond almost immediately to meteorological events. At the opposite extreme are objects with a stable regime (CV < 50%), such as Zubrzyca Dolna (28.88%), Babica (32.55%), or Koziarczyska (32.75%). Such low variability proves the high retention capacity of deeper aquifers, which are significantly less susceptible to short-term weather fluctuations.

From the perspective of sustainable water resource management, the high percentage of springs with high variability and episodic cessation of drainage highlights the vulnerability of shallow groundwater systems to hydrogeological droughts and progressive climate change. Under the conditions of growing climate pressure and increasing precipitation deficits, it is the deep aquifer structures with stable yields that play an important role.

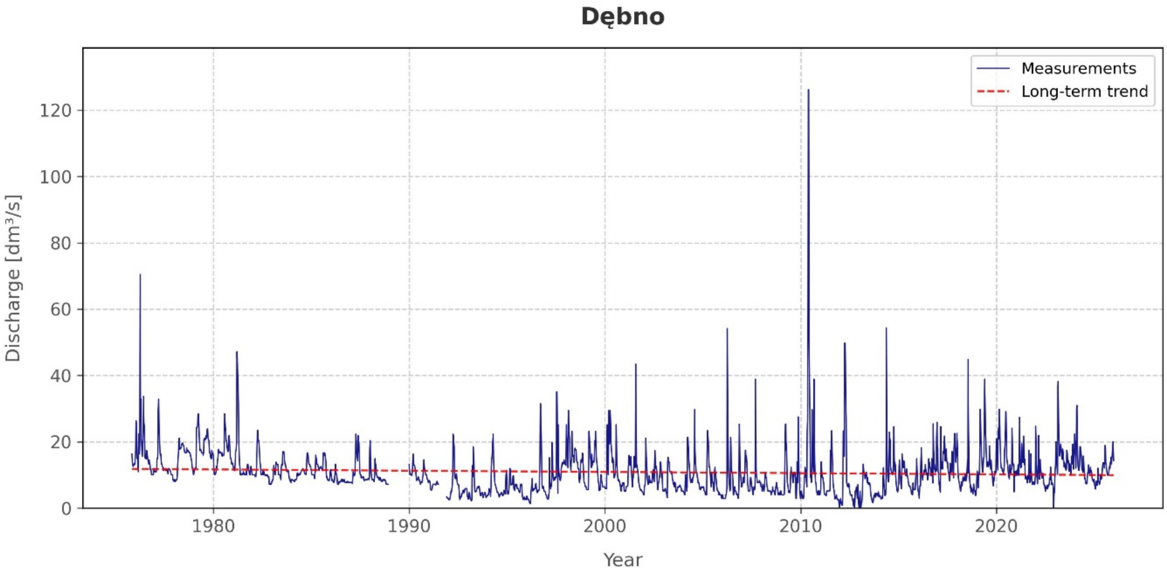
The visual analysis of long-term hydrograms (Figure 4a-d) provides crucial insights into the temporal dynamics of the studied springs, particularly regarding peak flows and episodic recharge events. For instance, the Kamesznica (Figure 4a) and Wetlina (Figure 4d) springs exhibit highly impulsive drainage patterns, characterized by abrupt discharge spikes reaching 10.00 dm^3/s and 2.00 dm^3/s, respectively, despite their relatively low base flows. Conversely, the Babica spring (Figure 4b) demonstrates a stable regime (0.09–0.96 dm^3/s), while Dębno spring (Figure 4c) shows extreme, rapid variations up to 126.18 dm^3/s in response to meteorological events.


Kamesznica
Measurements
Long-term trend
Discharge [dm³/s]
0
2
4
6
8
10
1988
1992
1996
2000
2004
2008
2012
2016
2020
2024
Year

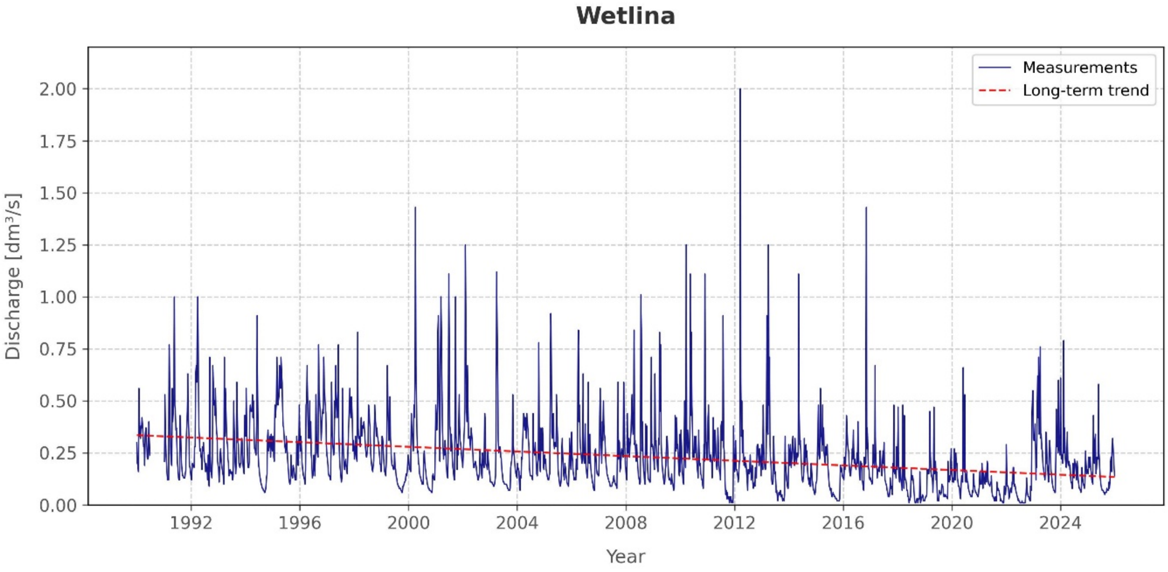
(a)


Babica
Measurements
Long-term trend
Discharge [dm³/s]
0.0
0.2
0.4
0.6
0.8
1.0
1988
1992
1996
2000
2004
2008
2012
2016
2020
2024
Year

(b)



(c)



(d)

Figure 4. Charts showing the variability in discharge of selected Carpathian springs (a) no. 3* Kamesznica (b); no. 7* Babica (c); np. 15* Dębno (d); no. 27* Wetlina (*points details shown in Table 1).

The long-term trend lines (Figure 4a–d) are significantly smoothed, thereby failing to reflect the true magnitude of these hydrodynamic processes. Consequently, assessing groundwater resources based solely on generalized trends is insufficient. A robust hydrogeological evaluation must prioritize temporal variability and cyclicity across seasonal and multiannual scales. These shorter-term fluctuations, which are largely masked by long-term trends, contain information for example rapid response of fractured systems to precipitation.

Ultimately, the observed amplitudes and frequency of discharge fluctuations expose the critical limitations of conventional, low-frequency manual monitoring. The inability of weekly measurements to accurately capture peak flow durations and the exact shape of recession curves robustly justifies the necessity of implementing automated telemetry systems. High-frequency data logging is essential to record the full spectrum of flow dynamics, thereby supporting reliable predictive modeling and the sustainable management of groundwater resources under increasing climate pressure.

3.2. Classification of the Springs Acc. to Standard Criteria

The complex nature of the springs under investigation and the need for a precise interpretation of the hydrodynamic processes occurring within them make it essential to classify them according to strictly defined criteria [45]. Proper identification of the specific characteristics of these discharges and the potential for adapting them to modern monitoring systems therefore requires reference to established spring classifications that allow for their systematization in geological, hydraulic and regime terms. Focusing on the specific characteristics of drainage in the Flysch Carpathians, this publication synthesizes classical categorizations with a modern analytical approach geared towards the needs of monitoring network automation. The complexity of the hydrogeological conditions in the Carpathians and the diversity of the structural and locational characteristics of the springs within the monitoring network of the Carpathian Branch of PIG-PIB necessitate the use of a multi-criteria assessment system. Only by combining the classical quantitative classifications according to Meinzer [46] with the genetic-structural classifications according to Pazdro [47] can a full understanding of the dynamics of the studied springs be achieved. Taking into account morphological features according to Keilhack [48], the type of bedrock and the lithology of the spring site is important for identifying technical barriers, such as ground instability or spring migration, which directly affect the feasibility of permanently installing telemetry equipment.

In order to organise the wide range of spring parameters within the studied monitoring network and to indicate the research potential of individual sites, a classification of 28 springs in the Carpathian monitoring network was carried out, classified according to the most common criteria mentioned above. The results of the analysis are summarized in Table 8.

3.2.1. Spring Discharge Criterion

Internationally, the most widely used classification of springs based on discharge rate is the Meinzers' classification [46], which divides springs into eight size classes, ranging from giant springs to trace springs (Table 2).

Table 2. Classification of springs by discharge rate [46, modified].

Size class	Flow rate [dm³/s]	Characteristics
I	> 2800	Giant springs (often karstic)
II	280 - 2800	Very large springs
III	28 - 280	Large springs
IV	6,3 - 28	Medium springs
V	0,63 - 6,3	Small springs
VI	0,06 - 0,63	Very small springs
VII	0,01 - 0,06	Faint (seeping) springs
VIII	< 0,01	Trace springs

In order to assess the classification of springs within the monitored network, a comparison was made between the average long-term flow rates and the categories listed in Table 1. This analysis revealed that, in the Flysch Carpathians, spring size classes VI and VII, as defined in [46], with the exception of the Tatra karst springs, which periodically achieve parameters qualifying them for the highest classes on this scale (Table 8). Of the springs analyzed in this study, as many as 68% are very small springs, whilst only 7% are large springs. Small and medium-sized springs account for 25%. Such a wide range of sizes necessitates the use of varied measurement methods.

3.2.2. Long-Term Variability Index Criterion Acc. Maillet [49]

For the Carpathian region, the classification based on the long-term variability index R according to Maillet [49] was considered particularly significant. The classification of the studied springs was carried out on the basis of a comparison of the obtained value of the R index, representing the ratio of extreme flow rates, i.e., the maximum flow rate Q_{max} to the minimum flow rate Q_{min}, observed over the long-term study cycle, with reference to Table 3.

Table 3. Classification of springs based on the long-term variability index R [49, modified].

Long-term variability index R	Characteristics
1-2	Stable springs
2-10	Slightly variable springs
10-50	Variable springs
> 50	Highly variable springs

An analysis of 28 springs operating within the Carpathian groundwater observation and research network, conducted on the basis of Maillet's classification of long-term variability [49], revealed a clear predominance of sites with high yield variability, as over 60% were classified as highly variable springs (R > 50), and 9 as variable (R = 10–50). These results fully correlate with the hydrogeological characteristics of the flysch Carpathians, where springs that react rapidly to precipitation and snowmelt recharge predominate. Only two sites in the analyzed group showed low variability (R = 2–10), suggesting a connection to more voluminous reservoirs or deeper circulation systems characterized by slower water exchange.

The widespread occurrence of high variability indices therefore provides a strong substantive argument for the need to automate measurements, as traditional manual observations are insufficient to capture extreme fluctuations in spring regime.

3.2.3. Long-Term Variability Index Criterion Acc. Meinzer [46]

Next, the variability of the studied springs was assessed using Meinzers's variability index V [38], which is an extension of Maillet's simple ratio (R) and determines the percentage deviation of the extreme yields from the long-term average yield according to equation (1):

$$V=100 \cdot (Qmax\text{-}Qmin)/Qśr, \tag{1}$$

The classification of analyzed springs was based on the classification presented in Table 4.

Table 4. Classification of springs based on the variation index V [38, modified].

V Index Value	Variability Class	Characteristics
< 25%	Steady	Very stable, with a deep circulation system. Little or no sensitivity to precipitation, etc.
25% – 100%	Sub-constant	Moderately variable. Typical of Polish highlands and foothills.
> 100%	Variable	Highly sensitive to precipitation, snowmelt, and droughts. Karst springs (caves) or "shallow" springs.

This analysis yielded an even more consistent description of the drainage dynamics of the studied springs than when using Maillet's R-index. All 28 of the analysed springs (100% of the studied population) were classified as variable springs, i.e., highly sensitive to rainfall, snowmelt and droughts. Thus, the results of this analysis confirmed and reinforced the view that it is necessary to automate spring discharge measurements within the studied monitoring network. Only by increasing the frequency of spring yield measurements and conducting an advanced analysis of the data collected over a long period of time will it be possible to make a realistic assessment of the nature of the spring and its regime, and to produce reliable forecasts.

3.2.4. Physical Criterion Acc. Keilhack [48]

A classification of springs based on physical criteria takes into account the driving force that causes groundwater to emerge at the earth's surface. The main driving forces are considered to be the force of gravity and hydrostatic pressure. On this basis, two main types are distinguished: descending (gravitational) springs, in which water flows downwards under the influence of gravity from the recharge area, and ascending (artesian) springs, where water moves upwards under the influence of hydrostatic pressure. This is the basic classification adopted, amongst others, by Keilhack [48].

In the case of the analyzed springs in the Carpathian part of the monitoring network, ascending springs account for a mere 11%. Gravity springs predominate, which is largely due to their morphological location.

3.2.5. Morphological Criterion

The classification of springs according to morphology is based on their location in relation to various landforms and constitutes one of the fundamental elements of hydrogeological description. The significance of this classification, which links morphology to geological structure, has been recognized in research practice for a century [47], and contemporary researchers of the Carpathians also demonstrate that the location of a spring (e.g., on a slope or in a valley) determines not only its yield, but above all its resistance to anthropogenic pressure and the dynamics of its response to precipitation [50]. The classification according to morphological criteria was carried out based on the types of springs listed in Table 5.

Table 5. Classification of springs based on terrain relief [47, 50, modified].

Spring type	Morphological location	Characteristics
Ridge and sub-ridge springs	The highest parts of hills and ridges.	They are often characterized by a small but steady discharge from the drainage of aquifers.
Slopes springs	The inclined surfaces of valley slopes and mountain slopes.	The most common type in mountainous areas; their dynamics depend heavily on the thickness of the weathered material and the slope of the terrain..
Valley springs	The bottoms of river valleys and depressions in the terrain.	They often drain deeper aquifers; they may take the form of channel outflows that feed directly into the river.
Edge springs	At the base of distinct steps and morphological edges.	They form in areas where the slope of the terrain changes abruptly; a variant of these are cliff springs found along coastlines.
Terraces springs	The edges and surfaces of river terraces.	They drain water from terrace alluvium; they often occur at the interface between permeable gravel and the impermeable terrace substrate.
Underwater springs	The bottoms of water bodies and rivers.	Outflows occurring below the water surface; the best-known types are channel springs (in riverbeds), lake springs, and submarine springs.
Landslide springs	Niches, channels, or landslide fronts; often found within colluvial deposits.	Water circulates through displaced rock masses; these systems are characterized by highly variable flow rates and are prone to rapid contamination.
Moraine springs	Landscapes shaped by ice sheets or mountain glaciers;	Formed from gravelly-sandy or stony moraines left behind by mountain glaciers and ice sheets.

	primarily valley-floor, terminal, and lateral moraines.	

An analysis of the 28 springs studied as part of the Carpathian monitoring network revealed a clear predominance of slope springs, which accounted for as much as 75% of all cases studied. Such a high proportion of this type of outflow is a direct reflection of the specific geological structure and morphology of the Flysch Carpathians, where alternating layers of permeable sandstone and impermeable shale are cut by the ground surface on sloping hillsides. In accordance with the commonly used classification [48], these features most often function as descending springs, where water flows freely under the influence of gravity at the points of contact between layers of varying permeability.

3.2.6. Criterion Regarding the Type of Hydraulic Hoses

In Polish hydrogeology, it is common practice to classify springs according to the type of hydraulic pathways through which groundwater flows [47]. This classification is regarded as one of the most important, as it is the nature of these water pathways that determines the flow rate, chemical composition and stability of drainage yield. According to this classification, three main types of springs are distinguished: porous (stratiform), fissure and karst (Table 6).

Table 6. Classification of sources by type of hydraulic pathways [47, modified].

Spring type	Characteristics	Regime and discharge variability
Porous (stratiform) springs	Water circulates in the intergranular pores of sedimentary rocks (e.g., sand, gravel).	It is characterized by high inertia and a stable flow rate; it is most often classified as a constant or nearly constant springs.
Fissure springs	The flow paths consist of weathering fissures, joints in compact igneous, metamorphic, and certain sedimentary rocks, as well as tectonic fractures in solid rock.	They exhibit high dynamics; their yield often increases sharply after rainfall, which classifies them as variable or highly variable springs.
Karst springs	Water flows through systems of channels, fissures, caves, and voids formed by karstification (rock dissolution).	They are characterized by the most dynamic flow regime and very high discharge rates (springs); they respond almost immediately to atmospheric precipitation.

In the network of 28 Carpathian springs studied, fissure springs are by far the most common (24 cases). This group is supplemented by three karst springs and just one pore spring. This configuration of genetic types is closely linked to the lithology of the flysch Carpathians, where the pathways of groundwater circulation consist primarily of fractures in solid rock. The dominance of fissure and karst conduits (27 sites in total) provides direct justification for the previously demonstrated extreme drainage dynamics.

3.2.7. Rock Type Criterion

In lithological classification, the primary criterion is the type of rock matrix through which groundwater flows (Table 7 – [47]). Rock springs occur in solid rock, where drainage takes place via systems of fissures, fractures or karst channels, which generally favours the concentration of the outflow. In contrast, cover springs, also referred to as springs in debris and weathered material, are located within Quaternary slope formations, landslide colluvia or alluvial cones. These features are characterized by a shallow circulation system within highly permeable material, which means that their yield is extremely variable and directly dependent on current weather conditions.

Table 7. Classification of springs by lithology [47, modified].

Spring type	Lithology	Characteristics of outflow and drainage
Rock springs	Compact rocks: sandstones, limestones, crystalline rocks.	Concentrated (point) discharge from unweathered rocks through systems of fractures, fissures, or karst channels.
Cover springs	Loose materials: slope clays, rock debris, gravel, sand.	Often diffuse drainage (puddles, seepage) within weathered material; highly dependent on current precipitation, snowmelt, and drought.

Of the springs analyzed in this study, which form part of the national groundwater observation and research network, as many as 23 are surface springs (approx. 82%). This predominance indicates that groundwater drainage in the study area occurs mainly within Quaternary cover consisting of loose formations, such as slope clays, rock debris or landslide colluvium, which is typical of the heavily denuded slopes of the Flysch Carpathians. The shallow circulation system in these formations means that water travels a short distance from precipitation infiltration to outflow, and the springs themselves are characterized by limited storage capacity.

3.2.8. Summary of the Application of Traditional Spring Classification Methods

The results of the classification of the monitored springs presented above, carried out in accordance with methodologies commonly used in similar analyses, are summarized in Table 8. To summarize the calculations and analyses performed, it was found that the lithological characteristics correspond closely with the morphological and hydraulic conditions of the study area. As many as 75% of the analyzed sites (i.e., 21 springs) are slope-based (slope) sites, which, combined with the fact that 27 out of 28 springs have fissure or karst-type conduits (Figure 5), defines their dynamic regime. The characteristics of drainage from shallow weathered cover are directly reflected in the results of the analysis. All 28 springs (100% of the studied population) were classified as variable springs according to Meinzera's classification [38], which constitutes substantive evidence of the inadequacy of traditional and, consequently, infrequent manual measurements. Under these conditions, the automation of the spring monitoring network is essential to reliably document rapid drainage responses to recharge and capture the actual dynamics of groundwater resources in the region.

Table 8. Summary of the classification of springs in the Carpathian Groundwater Observation and Research Network (PIG-PIB).

Spring no. per Figure 2	Name	Classification of springs by discharge rate	Long-term variability index criterion acc. Maillet	Classification of springs based on the variation index V	Physical criterion acc. Keilhack	Classification of springs based on terrain relief	Classification of sources by type of hydraulic pathways	Classification of springs by lithology
1	Ustroń-Dobka	small	highly variable	variable	descending	slopes spring	fissure spring	cover spring
2	Szyndzielnia	very small	highly variable	variable	descending	slopes spring	fissure spring	rock springs
3	Kamesznica	small	highly variable	variable	descending	edge spring	fissure spring	cover spring
4	Czernichów	very small	highly variable	variable	descending	slopes spring	fissure spring	cover spring

5	Żywiec-Koleby	very small	highly variable	variable	descending	slopes spring	fissure spring	cover spring
6	Ponikiew	very small	highly variable	variable	descending	slopes spring	fissure spring	cover spring
7	Babica	very small	variable	variable	descending	slopes spring	fissure spring	cover spring
8	Kraków-Kurdwanów	small	variable	variable	descending	edge spring	karst spring	rock springs
9	Bieńkówka	very small	highly variable	variable	descending	slopes spring	fissure spring	cover spring
10	Zawadka-Tokarnia	very small	highly variable	variable	descending	slopes spring	fissure spring	cover spring
11	Zubrzyca Dolna	very small	slightly variable	variable	descending	slopes spring	fissure spring	cover spring
12	Zakopane-Capki	large	highly variable	variable	descending	slopes spring	karst spring	rock springs
13	Koziarczyska	large	variable	variable	descending	edge spring	karst spring	cover spring
14	Białka Tatrzańska	very small	slightly variable	variable	descending	slopes spring	fissure spring	cover spring
15	Dębno	medium	highly variable	variable	ascending	valley spring	porous spring	cover spring
16	Falsztyn	small	highly variable	variable	descending	slopes spring	fissure spring	rock springs
17	Młynne	very small	highly variable	variable	descending	slopes spring	fissure spring	cover spring
18	Jaworki-Biała Woda	very small	highly variable	variable	descending	valley spring	fissure spring	rock springs
19	Rożnów	very small	variable	variable	descending	slopes spring	fissure spring	cover spring
20	Zbyszyce-Kurów	very small	highly variable	variable	descending	slopes spring	fissure spring	cover spring
21	Wierchomla	small	variable	variable	descending	slopes spring	fissure spring	cover spring
22	Kąty	very small	variable	variable	ascending	slopes spring	fissure spring	cover spring
23	Widacz	very small	variable	variable	ascending	slopes spring	fissure spring	cover spring
24	Radoszyce	very small	highly variable	variable	descending	slopes spring	fissure spring	cover spring
25	Sanok-Olchowce	very small	variable	variable	descending	valley spring	fissure spring	cover spring
26	Bystre-Rabe	small	variable	variable	descending	valley spring	fissure spring	cover spring
27	Wetlina	very small	highly variable	variable	descending	slopes spring	fissure spring	cover spring
28	Dwerniczek	very small	highly variable	variable	descending	slopes spring	fissure spring	cover spring

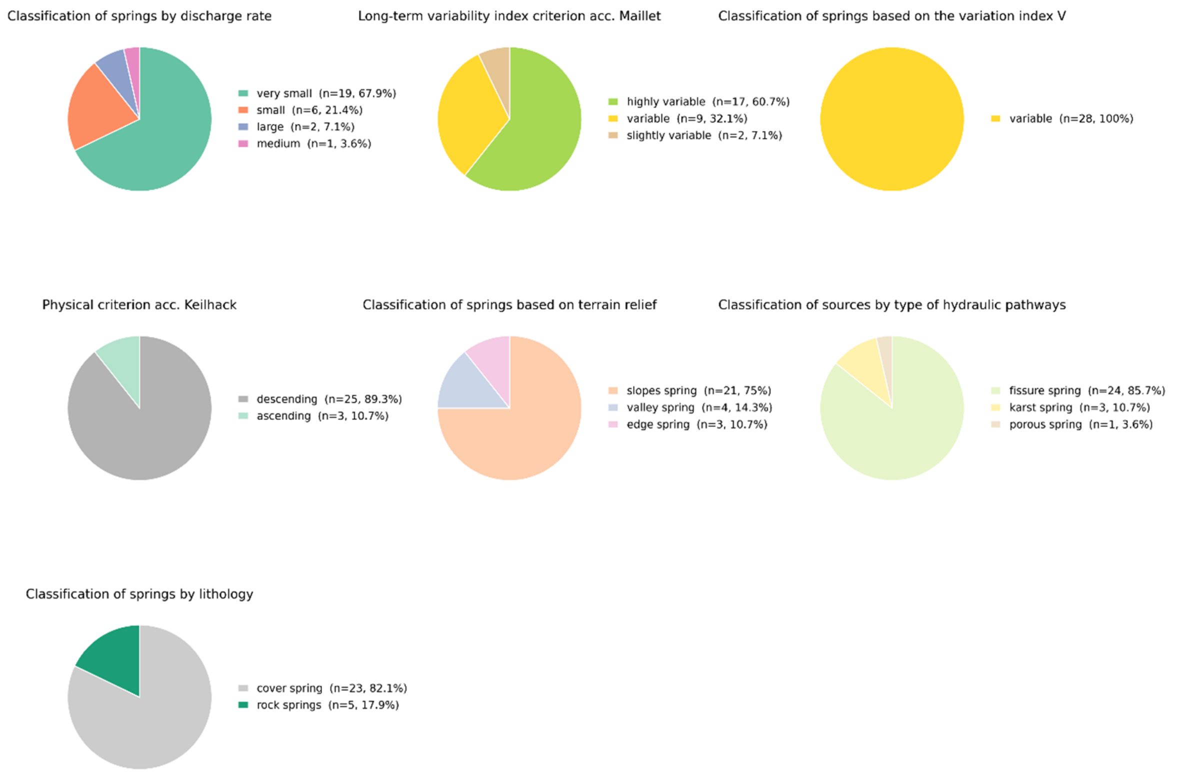


Figure 5. Summary distribution of the monitored springs according to traditional classification criteria acc. Table 8.

3.3. An Innovative, Proprietary Classification of the Springs Within the Monitoring Network

The implementation of the necessary automation of yield measurements for springs operating within the Polish groundwater monitoring network, as proposed in this publication, absolutely requires consideration of technical, logistical and administrative factors that are not analyzed in traditional studies. For this reason, this paper proposes four new, original classifications that bridge the gap between the theoretical characteristics of a spring and the practical feasibility of implementing telemetry systems in them. The proposed classifications allow for an objective assessment of the degree of difficulty of installation work and the identification of formal and legal barriers, resulting, among other things, from conflicts with protected areas.

The following table presents an innovative and original example of a classification scheme in which all springs monitored within the Polish groundwater monitoring network of the Outer Carpathians have been assessed for their potential to implement automated measurements. This is of paramount importance in the studied region of the flysch Carpathians, where aquifers are characterized by an exceptionally short response time to infiltration; as indicated earlier, the potential implementation of automated systems capable of recording the full range of yield variability in continuous mode (or with a high measurement frequency) will enable the effective recording of these changes. This will thus enable advanced data analysis, taking into account seasonal or even daily variations, as well as the formulation of forecasts.

In order to optimize the implementation processes of modern measurement methods, this paper proposes four innovative and original classifications of springs that take into account ‘non-hydrogeological’ barriers.

3.3.1. The Proposed ‘F’ Classification Based on Formal, Legal and Ownership Criteria

The first classification concerns formal, legal and ownership conditions; designated as ‘Classification F’, it will form the basis for planning a long-term monitoring strategy, based on the criteria of durability and safety of the research infrastructure. Within this framework, three levels of stability for the location of a measuring point have been proposed (Table 9).

Table 9. ‘F’ classification based on formal, legal and ownership criteria.

Category F	Description
F1	High stability
F2	Limited stability
F3	Outdoor use

Category F1 (high stability) should include springs located on state-owned land, or alternatively within the administration of authorized bodies (national parks, state forests), where a regulated legal status and transparent administrative procedures guarantee a minimal risk of sudden interruption to the continuity of observations.

The proposed Category F2 (limited stability) presents a significantly greater operational challenge and covers springs located on private land made available for monitoring on the basis of fixed-term lease or loan agreements. Such locations require periodic renegotiation; moreover, in this case, unforeseen changes in ownership are possible.

The highest level, i.e., category F3 (outdoor use), applies to facilities that serve a practical purpose for their owners and/or local communities; this necessitates adapting automation technology to its primary supply function, sometimes limiting the scope for intervention in the design and infrastructure of the monitoring spring in question.

3.3.2. The Proposed ‘T’ Classification Based on Criteria for Readiness to Implement Measurement Automation

The proposed innovative classification, denoted by the symbol ‘T’, is based on an assessment of the technical and structural readiness for the automation of spring performance measurements. The application of this classification will enable an objective assessment of the existing infrastructure (Table 10) and, consequently, will allow for an estimation of the necessary investment expenditure and the scope of adaptation work required for the effective implementation of automated systems at a given point in the monitoring network.

Table 10. ‘T’ classification based on criteria for readiness to implement measurement automation.

Category T	Description
T1	Fully ready
T2	Requires adaptation
T3	Not ready

The innovative T classification introduces three categories, where T1 (fully ready) covers sites with stable and secure technical infrastructure that provides sufficient space for the installation of recorders and antennas and ensures effective protection of the equipment against external factors (pre-modernized sites). Category T2 (requires adaptation) refers to poorly secured sites where there is no stable measurement cross-section. At these locations, engineering and technical work is required (e.g., construction of a measurement platform) and a secure installation site must be provided to protect the equipment from vandalism and the effects of weather conditions. Category T3 (not ready) covers springs with the lowest implementation potential, situated in unfavorable terrain conditions, on steep slopes, directly in stream beds, on steep, unstable embankments, or in areas with a complete lack of GSM coverage (in so-called communication dead zones). Implementing telemetry in these locations precludes a standard approach.

3.3.3. The Proposed 'S' Classification Based on the Method of Capturing Them and Technical Infrastructure

The third proposed innovative classification of springs based on method of capturing them is based on the type of technical infrastructure currently in place at the spring, which directly influences the selection and applicability of flow measurement methods and telemetry technology.

The following five methods of capturing the spring were identified: pipe intake (the outflow is captured directly by a discharge pipe), weir intake (a concrete barrier erected across the outflow to dam up the water, which is discharged through a pipe), an intake chamber (various types of tanks and boxes collecting water from the spring with a discharge pipe), a measuring weir (springs with a permanent barrier built in, featuring a cut-out measuring opening), and a ring casing (a spring enclosed within a vertical series of concrete rings with a discharge pipe).

Table 11. 'S' classification based on the method of capturing them and technical infrastructure.

Category 'S'	Descripion
S1	Pipe intake
S2	Weir intake
S3	Intake chamber
S4	Measuring weir
S5	Ring casing

3.3.4. The Proposed 'N' Classification Based on Criteria Relating to Conflicts with Protected Areas

The latest proposed, innovative and hitherto unused 'N' classification is based on an assessment of nature conservation regimes and environmental constraints relating to potential conflicts arising from the implementation of spring automation in light of the objectives of designated protected areas. Given the location of the sites under study in regions of high natural value, it seems essential to introduce the proposed separate classification based on forms of nature conservation. The regime of protected areas directly determines the scope of possible engineering works, the type of equipment masking used, and the timeframe for administrative processes related to obtaining permits for infrastructure modernization. Within this classification system, four categories have been identified: N1, N2, N3 and N4 (Table 12).

Table 12. 'N' classification based on criteria relating to conflicts with protected areas.

Category N	Description
N1	High protection level
N2	Medium protection level
N3	Point protection
N4	No protection

Category S1 - high protection level; this covers springs located within national parks and nature reserves, where the installation of automatic flow measurement devices requires individual consent from nature conservation authorities and is often subject to restrictions on equipment (prohibition of visible antennas, requirement for natural casings) and limitations on the use of photovoltaic panels.

Category S2 – medium protection level, covering springs located within landscape parks, NATURA 2000 sites and protected landscape areas, where the focus is on protecting groundwater-dependent ecosystems (GDE). The implementation of automated measurements of spring flow rates requires consultation with regional environmental protection authorities, although the forms of protection usually necessitate non-invasive methods of sensor installation that do not disrupt the natural drainage regime.

Category S3 – point protection – applies to situations where the spring itself is a legally protected site, i.e., most commonly a natural monument. Any interference with the spring basin or the concreting of the spring thresholds is prohibited, which directly dictates the choice of a non-contact measurement method (e.g., radar loggers suspended above the water surface).

The final category, S4 – areas with standard environmental conditions – covers sites located outside designated protected areas, where the development process is subject to general legal provisions regarding environmental protection, water use and the conduct of construction works.

3.3.5. Summary of the Proposed Innovative Classifications of Springs

The proposed proprietary classifications F, T, S and N are highly versatile, allowing for their widespread implementation beyond the scope of the Polish groundwater spring monitoring network. These classifications can be successfully used in the design of automation systems for any springs forming the basis of water supply for local waterworks, testing points or springs of environmental importance. Given that the proposed classification criteria focus on objective technical, ownership and site-specific barriers, this classification system has significant potential for international implementation. Only classification S (based on nature conservation regimes and environmental restrictions) would require minor adaptations to the legislative conditions and nomenclature of protection measures in force in other countries. Nevertheless, whilst maintaining the same gradation of protection levels, the proposed criterion could serve as a universal tool in the process of automating spring discharge measurements, with the aim of increasing their frequency and thereby enabling the conduct and analysis of real-time, comprehensive observations covering the full range of their natural variability. The results of the proposed proprietary classifications of the monitored springs presented above, are summarized in Table 13.

Table 13. Summary of the proposed proprietary classifications of springs in the Carpathian Groundwater Observation and Research Network (PIG-PIB).

Spring no. per Figure 2	**Name**	**‘F’ classification based on formal, legal and ownership criteria**	**‘T’ classification based on criteria for readiness to implement measurement automation**	**‘S’ classification based on the method of capturing them and technical infrastructure**	**‘N’ classification based on criteria relating to conflicts with protected areas**
1	Ustroń-Dobka	high stability	requires adaptation	weir intake	medium protection level
2	Szyndzielnia	outdoor use	requires adaptation	pipe intake	medium protection level
3	Kamesznica	high stability	requires adaptation	intake chamber	no protection
4	Czernichów	high stability	not ready	weir intake	no protection
5	Żywiec-Koleby	high stability	requires adaptation	intake chamber	no protection
6	Ponikiew	limited stability	requires adaptation	weir intake	medium protection level
7	Babica	limited stability	requires adaptation	ring casing	no protection
8	Kraków-Kurdwanów	outdoor use	requires adaptation	intake chamber	no protection

9	Bieńkówka	outdoor use	requires adaptation	intake chamber	no protection
10	Zawadka-Tokarnia	outdoor use	requires adaptation	intake chamber	no protection
11	Zubrzyca Dolna	limited stability	requires adaptation	weir intake	no protection
12	Zakopane-Capki	limited stability	requires adaptation	measuring weir	no protection
13	Koziarczyska	high stability	fully ready	measuring weir	high protection level
14	Białka Tatrzańska	limited stability	requires adaptation	weir intake	no protection
15	Dębno	limited stability	fully ready	measuring weir	medium protection level
16	Falsztyn	outdoor use	requires adaptation	intake chamber	medium protection level
17	Młynne	outdoor use	requires adaptation	weir intake	no protection
18	Jaworki-Biała Woda	high stability	requires adaptation	weir intake	high protection level
19	Rożnów	high stability	requires adaptation	ring casing	medium protection level
20	Zbyszyce-Kurów	outdoor use	requires adaptation	intake chamber	no protection
21	Wierchomla	limited stability	requires adaptation	ring casing	medium protection level
22	Kąty	outdoor use	requires adaptation	ring casing	medium protection level
23	Widacz	outdoor use	requires adaptation	pipe intake	no protection
24	Radoszyce	limited stability	requires adaptation	ring casing	no protection
25	Sanok-Olchowce	outdoor use	requires adaptation	weir intake	medium protection level
26	Bystre-Rabe	high stability	requires adaptation	weir intake	medium protection level
27	Wetlina	outdoor use	requires adaptation	weir intake	medium protection level
28	Dwerniczek	outdoor use	requires adaptation	weir intake	medium protection level

4. Discussion

The results obtained in this study clearly demonstrate that springs located within the flysch Carpathians represent highly dynamic hydrogeological systems, characterized by rapid responses to precipitation and limited storage capacity. This behavior is consistent with previous studies conducted in mountainous and fractured aquifers, where groundwater circulation is dominated by shallow flow systems and short residence times, resulting in highly variable discharge regimes [41–44,50]. Similar conclusions have been reported for mountain regions worldwide, including the Alps and other European highlands, where springs act as sensitive indicators of short-term hydroclimatic variability.

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The dominance of highly variable springs (R > 50) identified in this study confirms that traditional monitoring approaches based on weekly manual measurements are insufficient to capture the full spectrum of discharge fluctuations. This limitation has been widely recognized in recent hydrological research, which emphasizes that low-frequency datasets may lead to substantial underestimation of peak flows and misinterpretation of recharge processes [51,52]. In highly dynamic systems such as fissured and karst aquifers, hydrological responses to precipitation may occur on timescales of hours to days, rendering conventional observation intervals inadequate [38,40].

The results of the Meinzer variability index (V), which classified all analyzed springs as variable, further reinforce the necessity of implementing automated monitoring systems. Comparable findings have been reported in studies of karst and mountain aquifers, where continuous monitoring has proven essential for identifying recession characteristics, storage properties, and recharge dynamics [41,42]. Moreover, high-frequency monitoring has been shown to significantly improve the understanding of hydrological processes and reduce uncertainty in water balance assessments [53,54]. In this context, the Carpathian springs can be considered representative of a broader class of hydrogeological systems requiring modernization of monitoring strategies.

An important contribution of this study is the identification of non-technological barriers as the primary limitation to the implementation of telemetry systems. While recent technological developments, including low-cost sensor networks and automated data transmission, have significantly increased the feasibility of high-frequency monitoring [55], their practical implementation is often constrained by legal, administrative, and environmental factors. Similar challenges have been identified in groundwater governance studies, which highlight the role of institutional complexity, land ownership, and regulatory frameworks as key limiting factors [56,57]. This finding underscores the need to move beyond purely technical solutions and adopt integrated approaches to monitoring network development.

The proprietary classification system proposed in this study (F, T, S, N) represents a novel methodological contribution that extends traditional hydrogeological classifications. By incorporating formal-legal, technical, and environmental criteria, the proposed framework addresses a critical gap in existing approaches, which typically focus exclusively on physical characteristics of springs. This aligns with broader trends in hydrogeology and water resource management, emphasizing the importance of integrating scientific, technical, and governance dimensions [3,6]. Comparable integrative approaches have been proposed mainly in the context of surface water monitoring system design [58], highlighting the innovative nature of applying such concepts to groundwater spring monitoring.

From a broader perspective, the findings of this study are highly relevant in the context of climate change and increasing hydrological variability. Recent studies indicate that shifts in precipitation patterns and the growing frequency of extreme events significantly affect groundwater recharge and discharge dynamics [5,8]. Springs, due to their integrative character, may serve as early indicators of both drought development and rapid recharge events, providing valuable information for adaptive water resource management. In this regard, the role of springs as “natural sensors” of aquifer response is increasingly recognized in contemporary hydrogeological research.

Furthermore, the results highlight that optimizing monitoring networks should focus not only on increasing the number of observation points but primarily on improving data quality and temporal resolution. This conclusion is consistent with recent recommendations advocating the development of “smart monitoring networks” that integrate high-frequency measurements, remote sensing data, and advanced analytical tools [17,59]. In such systems, springs may complement borehole-based monitoring by providing cost-effective and hydrologically representative observation points.

The integration of high-frequency monitoring data with advanced modeling techniques, including machine learning approaches, represents a promising direction for future research. Recent studies demonstrate that data-driven models can significantly enhance the prediction of groundwater dynamics, particularly in complex and data-scarce environments [60]. In combination with automated monitoring systems, such approaches may substantially improve the forecasting of hydrological extremes and support more effective groundwater management.

Future research should focus on the practical implementation of automated monitoring systems at selected representative springs, particularly those characterized by favorable technical and legal conditions (e.g., F1 and T1 categories). It is also recommended to integrate spring discharge data with meteorological observations and satellite-based datasets to improve the understanding of recharge processes and system responses. Finally, the applicability of the proposed classification framework should be tested in other hydrogeological settings, including karst regions and lowland aquifers, to assess its universality and potential for broader implementation..

5. Conclusions

Groundwater springs are exceptionally valuable observation and research points, often referred to as ‘natural windows’ into aquifer systems. They provide integrated information on the state of the entire recharge and discharge system, and their response to climatic and anthropogenic changes is usually faster than that of conventional observation points based on boreholes. For this reason, the monitoring of springs plays a significant role in assessing groundwater storage, forecasting the hydrogeological situation and planning rational water management.

An analysis of springs operating in the Carpathian part of the national groundwater observation and research network has shown that the vast majority of them are characterized by very high yield variability and a short response time to rainfall recharge. Under such conditions, manual measurements taken on a weekly basis do not allow for the full range of flow dynamics to be captured, nor for the correct interpretation of dynamic resources. Consequently, this may lead to an underestimation of extreme flow values and errors in the analysis of hydrogeological processes.

The multi-criteria analysis of springs carried out in this study has shown that the main barrier to the implementation of automatic monitoring systems is not a lack of measurement technology, but non-hydrogeological factors, such as land ownership status, restrictions arising from nature conservation, or the technical condition of the existing infrastructure. For this reason, a proprietary classification system has been proposed, covering formal-legal, technical-structural and environmental criteria, which enables the assessment of the realistic possibilities for installing telemetric systems at specific points in the network.

The research findings indicate that the optimization of groundwater monitoring in the Carpathians should focus not so much on increasing the number of observation points, but rather on the gradual introduction of automated measurement systems at representative locations. High-frequency telemetry data will allow the full variability of spring yields to be captured, which forms the basis for the development of reliable predictive models and the effective management of groundwater resources in the face of increasing climate variability.

The classification approach proposed in this study is universal in nature and can also be applied in other mountainous regions with similar hydrogeological conditions. In this context, the Flysch Carpathians may serve as a model study area for the development of modern groundwater spring monitoring systems in Europe.

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Abbreviations

The following abbreviations are used in this manuscript:

PIG-PIB	Polish Geological Institute – National Research Institute
GWBs	Groundwater bodies
WFD	Water Framework Directive
LD	Linear dichroism

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