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Assessment of different types of anthropopressure on selected karst springs in Poland – implementation of the MIKAS project (Most Important Karst Aquifer Springs)

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ABSTRACT:

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The aim of this study is to assess the impact of various forms of anthropogenic pressure on selected karst springs in Poland, regarded as elements of "natural heritage": Blue Springs, Goryczkowe Vauclusian Spring, and Zygmunt Spring. These springs are located in different regions of Poland and represent the most efficient karst springs in their respective areas, distinguished by exceptional aesthetic values and have been recognized as natural heritage sites and included in the international *Most Important Karst Aquifer Springs* (MIKAS) database or its national counterpart (NIKAS). A key factor differentiating these springs is the type of anthropogenic pressure exerted upon them. In the case of Blue Springs, located in central Poland near Tomaszów Mazowiecki, anthropopressure is manifested through modifications to the hydrological network and flow conditions due to attempts to extract groundwater for the municipal water supply of Łódź. Goryczkowe Vauclusian Spring, located in southern Poland within the Tatra National Park, is subject to indirect anthropogenic impact primarily via atmospheric deposition of pollutants originating from industrialized regions outside the park. For Zygmunt Spring, located in southern Poland, the dominant form of anthropopressure is intensive tourism. Despite its status as a nature reserve, the area has suffered from a reduction in biodiversity and poor water quality, particularly in terms of bacteriological status. Despite ongoing pro-environmental efforts, environmental changes around all the studied springs are evident and scientifically confirmed. Although the springs' location within parks or reserves does not shield them from long-range atmospheric pollution, it does provide a level of protection by limiting both water usage and land development, generally restricted to tourism and sightseeing. Nevertheless, risks associated with tourism management must be acknowledged, including increased water demand, wastewater and solid waste generation, as well as non-compliance with regulations governing protected areas (e.g., destruction of unique vegetation).

Key words: Karst spring; Anthropopressure; MIKAS project; SWOT analysis.

INTRODUCTION

Karstified carbonate rocks, in which networks of karst conduits and caves play a fundamental role in groundwater circulation, cover approximately 12% of the Earth's surface. Due to the typically high discharge rates of karst springs, they hold significant economic importance as sources of drinking water (Meng *et al.* 2016; Chen *et al.* 2017; Zare *et al.* 2024). It is worth noting that springs functioning in various geological environments serve as primary sources of potable water in many countries (Ansari *et al.* 2015). Given the specific flow systems within karst environments and the unique characteristics of individual springs, it is crucial to develop conceptual models of groundwater dynamics for each spring's catchment area. In addition, continuous monitoring of both flow dynamics and water chemistry is essential (Wcisło *et al.* 2014; Pratama *et al.* 2021; Deng *et al.* 2022; Bojarczuk *et al.* 2024; Pinza *et al.* 2024), with particular attention to the high vulnerability of karst waters to contamination (Moreno-Gomez *et al.* 2024).

The quality of spring waters – especially those from karst systems – can be degraded due to anthropogenic pressures (Geyer *et al.* 2007; Adesakin *et al.* 2020; Peng *et al.* 2025), posing potential health risks to consumers (Paikary and Mahajan 2023; Deng *et al.* 2024). The well-known group of karst springs in Jinan has been studied for nitrate contamination (Gao *et al.* 2020), sulfur compounds (Jie Zhang *et al.* 2021), and variations in discharge and water chemistry (Wang *et al.* 2023), while the spring area of the Zihe River was examined by You *et al.* (2024). An emerging research direction involves the analysis of preferential flow and its interactions with soil and vegetation in karst regions (Gromadzka *et al.* 2015; Guan *et al.* 2024). Karst systems have also become subjects of investigation for their role in CO_2 sequestration by carbonate rocks, viewed through the lens of climate change mitigation (Li *et al.* 2024; Zhang *et al.* 2024).

Due to the diverse and often site-specific nature of issues associated with karst springs, the need for their systematic inventory and monitoring has been recognized as essential for their protection. In response, two international initiatives have been launched: the *World Karst Aquifer Mapping Project* (WOKAM) and the *Most Important Karst Aquifer Springs* (MIKAS). Between 2012 and 2015, the WOKAM project – coordinated by the Karst Commission of the International Association of Hydrogeologists – was carried out Różkowski served as the national coordinator for Poland. The goal of the WOKAM project was to create the first global map of karst aquifers, illustrating outcrops of carbonate rocks, deep and buried karst aquifers, major karst springs, groundwater abstraction points, and caves that meet the primary criterion of discharge capacity (Chen *et al.* 2017).

The selection criteria for springs included in the general database were as follows: for permanent springs, a minimum discharge of >200 L/s; for intermittent springs or those with high variability, >10 m³/s. In a subsequent stage of spring selection, the key criterion became the estimated minimum annual discharge – base flow (QLF) – divided into two classes: QLF ≥2 m³/s and QLF <2 m³/s, while also considering their regional importance. This allowed for the inclusion of hydrogeological features with lower discharges into the database (Chen *et al.* 2017).

According to the WOKAM map, the largest karst spring systems include: (1) Nacimiento de Rio Frio (Spain) (Q_{max} = 515 m³/s), Buna (Bosnia and Herzegovina), (Q_{max} = 380 m³/s), and Nacimiento del Rio Mante (Mexico), (Q_{max} = 343 m³/s), (2) submarine karst springs: Crescent Beach (USA), Q_{Low} = 40 m³/s; Pantai Ngrenehan (Indonesia), Q_{Low} = 8 m³/s, and thermal karst springs – Devnya Spring (Bulgaria), Q_{max} = 4 m³/s (Chen and Goldscheider 2017).

The database also includes springs from the territory of Poland: five vaucluse-type springs from the Tatra Mountains (Chochołowskie, Lodowe, Bystra, Goryczkowe, and Olczyskie), springs in Julianka-Sygontka in the Kraków-Częstochowa Upland, and the Zaporze Spring in the Lublin Upland (Różkowski *et al.* 2015). Taking into account their regional significance, the WOKAM map identifies three karst features in Poland, including one karst spring in Julianka-Sygontka with a discharge of Q_{max} = 0.6 m³/s (Chen and Goldscheider 2017).

The *Most Important Karst Aquifer Springs* (MIKAS) project is a continuation of the *World Karst Aquifer Mapping Project* (WOKAM). It was inaugurated during the Karst Commission meeting of the International Association of Hydrogeologists (IAH) at the EUROKARST conference in Malaga in 2022. The goal of the project is to promote karst springs both scientifically and as tourist destinations, while simultaneously ensuring their protection from degradation. In addition to the project's website, a monograph is being prepared, summarizing the results and listing approximately 200 springs of global significance (MIKAS) and national significance (NIKAS), proposed by experts from various countries and accepted by an Advisory Committee composed of members from the IAH Karst Commission and UNESCO specialists. Spring selection is based on the following criteria: historical (H) – considers the role of the spring in the development of the surrounding region, as well as its influence on art, culture, and customs, including utilitarian and scientific interest; aesthetic (A) – supports the promotion of the spring and its region as a geotourism attraction; economic (E) – evaluates whether the spring is or was used for economic purposes (e.g., drinking water supply, mechanical power generation, balneological use) and whether this use has influenced the hydrogeological regime; scientific (S) – considers the state of knowledge about the hydrogeological regime, water chemistry, ecosystems within the spring zone, and the duration and scope of scientific research and monitoring; and Ecological (Es) – evaluates whether the spring and associated watercourse are located within legally protected areas. The spring characterization questionnaire gathers the required basic information that allows for the localization and initial hydrogeological understanding of the spring (e.g., discharge, variability, water quality and use), as well as the optional data on water chemistry and threats, supported by supplementary graphical material. As a result of the work conducted by the Polish team – including Różkowski (national coordinator), Chwalik-Borowiec, Okoń, Sposób, Barczyk, Chmiel, Małecki, and Turczyński – karst springs and Vaucluse-type springs from Poland were submitted to the MIKAS and NIKAS databases. These include: (1) from the Tatra Mountains: Lodowe, Goryczkowe, Bystra, Chochołowskie, and Olczyskie springs; (2) from the Lublin Upland and Roztocze region: Krasnobród Spring, Wąwolnica Spring, and Zaporze Spring; (3) from the Nida River Basin: Winiary Spring and Zimne Doły Spring; (4) from the Kraków-Częstochowa Upland: springs in Julianka-Sygontka, Hydrografów Spring, and Zygmunt Spring; and (5) from the Polish Lowlands: Blue Springs in Tomaszów Mazowiecki. The springs of the Lublin Upland and Roztocze are associated with Cretaceous formations such as siliceous limestones, marls, marly limestones, and gaizes. Springs in the Nida River Basin are related to Neogene gypsum deposits, while the remaining springs are primarily associated with Jurassic and Triassic carbonate formations (Barczyk *et al.* 2024).

Utilizing data from the aforementioned databases as well as original research, an assessment was conducted on three selected springs to evaluate their anthropogenic changes over time. The aim of this paper is to assess the impact of various types of anthropogenic pressure on selected karst springs in Poland, treated as elements of *natural heritage* (a term proposed and adopted during the UNESCO Paris Convention in 1972, which Poland ratified in 1976). Among the environmentally valuable springs, the following were selected for analysis: Blue Springs, Goryczkowe Vaucluse Spring, and Zygmunt Spring. The selection was based on the following criteria: karstic character of the aquifer, geographic distribution across different regions of the country, highest spring discharges in the catchment of Poland, long-term monitoring data, and the confirmed occurrence of diverse anthropogenic impacts at the spring outlets.

TERMINOLOGY AND METHODOLOGY

In English-language scientific literature, natural, spontaneous, and concentrated groundwater outflows in karst areas are referred to as *karst springs*, while pressurized (ascending) flows are termed *exsurgent springs* or *vauclusian springs*. The latter term originates from the famous Fountain de Vaucluse in France. In Slavic-language literature, springs with a similar discharge mechanism are referred to as *wywierzyska* (or *vyvěračka* in Czech) (Panoš 2001). According to Barczyk (2008), the term *wywierzysko* refers to: a permanent or intermittent karst spring with a long-term average discharge exceeding 100 L/s, emerging under pressure and fed primarily by autochthonous karst water circulating through a system of fissures and karst voids within the rock mass. The springs selected for analysis were chosen based on data from the MIKAS and NIKAS databases and the criteria stated above (karstic nature of the aquifer, occurrence in different regions of Poland, highest spring discharges in the country, long-term monitoring studies, confirmed anthropogenic influence at the spring site, and diversity of anthropogenic factors). In all cases, the aquifers are composed of carbonate rocks, and water flow along with spontaneous discharge to the surface occurs via a network of interconnected karst conduits.

The analyzed springs represent different geographic regions of Poland: Lowland region: Blue Springs; Upland region: Zygmunt Spring; Mountain region: Goryczkowe Vaucluse Spring.

All of them exhibit the highest discharge rates within their respective areas and are supported by long-term research data, allowing for the identification of temporal trends in environmental changes caused by land use modifications and anthropogenic influences.

LOCATION OF THE STUDIED SPRINGS

Blue Springs (listed in the NIKAS database) are located in central Poland, in the town of Tomaszów Mazowiecki (Text-fig. 1). They are situated in the geographical province of the Central European Lowland, specifically within the Central Polish Lowlands subprovince. The spring belongs to the Pilica River catchment, which is part of the Vistula River basin. The geographic coordinates of the spring are: 51°30’37.98”N, 20°01’28.08”E.

Blue Springs, as a unique karst site in the Polish Lowlands, are protected within the “Niebieskie Źródła” (Blue Springs) nature reserve, which covers an area of 28.7 hectares (established in 1961). The site lies within the buffer zone of the Sulejów Landscape Park and is also part of the Natura 2000 area “Niebieskie Źródła” (PLH100005).

Goryczkowe Vaucluse Spring (listed in the MIKAS database) is located in southern Poland and administratively belongs to the city of Zakopane (Text-fig. 1). Geographically, it is situated in the Western Tatras, within the Western Carpathians and Subcarpathia geographic province, and more specifically, the Central Western Carpathians subprovince. The Tatra Massif within Polish borders lies entirely within the Tatra National Park. The spring is located on the northwestern slopes of Myślenickie Turnie. Goryczkowe Vaucluse Spring serves as the headwater for the Goryczkowy Stream, which is part of the Bystra Stream catchment and, ultimately, the Vistula River basin. The spring’s geographical coordinates are: 49°15’15”N, 19°58’21”E.

The spring is not actively exploited, and therefore, no designated sanitary protection zone has been established; however, it is protected within the boundaries of the Tatra National Park (since 1955). Water emerges from a scarp above the dry streambed and occasionally appears within the channel itself during certain periods. Approximately 10 meters downstream from the main discharge point, water is extracted to supply drinking water to several nearby tourist facilities (including a cable car station Kasprowy Wierch) (Text-fig. 1). For the aforementioned intake, a protection zone was originally designated; however, since the mid-1980s, it has been protected under the status of the national park. The discharge area of the Goryczkowe Vaucluse Spring lies outside the network of tourist trails maintained by Tatra National Park (TPN), although the recharge area, covering approximately 3 km², is intersected by numerous hiking trails. After merging with the Bystra Stream, the waters of the Goryczkowy Stream supply a surface water intake that provides drinking water for the town of Zakopane.

Zygmunt Spring (listed in the MIKAS database) is located in southern Poland, in the village of Złoty Potok (Text-fig. 1). Geographically, it is situated within the Polish Uplands province, specifically in the Silesian-Kraków Upland subprovince. Zygmunt Spring forms the headwaters of the Wiercica River, a right-bank tributary of the Warta River, and thus belongs to the Odra River basin. The geographic coordinates of the spring are: 50°41’15.96”N; 19°24’44.57”E.

The spring is not exploited, and therefore no sanitary protection zone has been established. Zygmunt Spring is protected as part of the “Parkowe” Nature Reserve (since 1957), the Eagles’ Nests Landscape Park, and the Złotopotocka Natura 2000 site (PLH240020) (Text-fig. 1) (Baścik and Okoń 2022).

RESULTS AND DISCUSSION

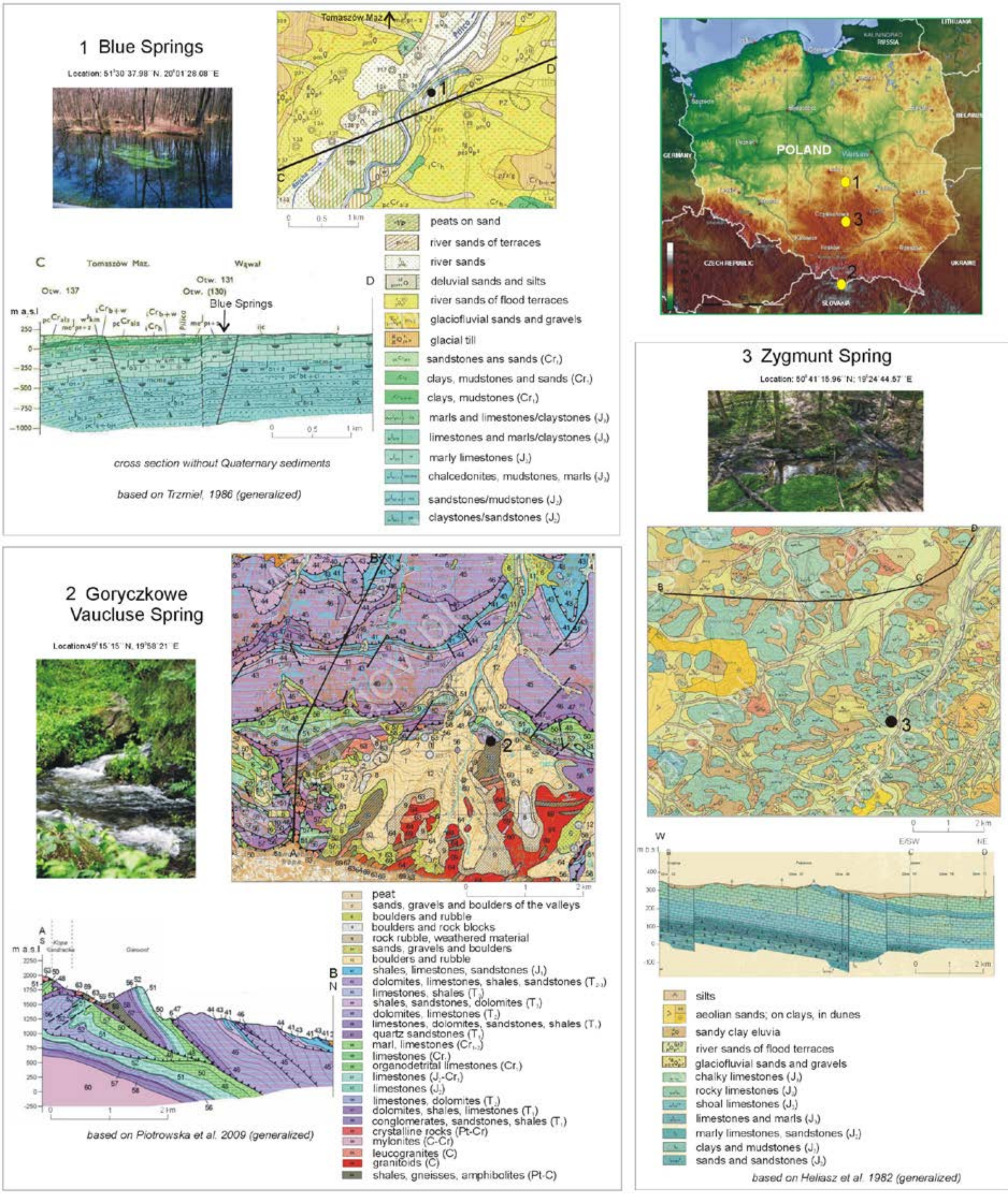
Representative Springs under Anthropogenic Pressure

Blue Springs

Hydrogeological Characteristics. Blue Springs are perennial karst springs located on the floodplain terrace of the Pilica River, at an elevation of 154 m a.s.l. These are ascending-type springs (with recharge water emerging from a depth of 34 m), classified as fissure-karst, fault-controlled, and barrier-type springs. They form a limnocrene system – comprising a flooded area with small islands (three lake basins). The springs lie within the drainage zone of the Upper Jurassic aquifer, which is composed of limestones. The overlying strata consist of Cretaceous clays, gaizes, and sandstones, as well as Quaternary sands and gravels.

The discharge regime of the karst spring, studied between 1951 and 1990, was as follows: minimum, average, and maximum discharges were 21/ 87/240 L/s, respectively. The discharge variability index ($R = Q_{max}/Q_{min}$) ranged from 2 to 8 (Małecka and Małecki 1998). Between 2007 and 2009, discharge ranged from 60 to 140 L/s, with an average of 77 L/s; the variability index (R) ranged from 1.85 to 2.33 (Koślacz *et al.* 2010).

Periodic studies of the physical-chemical properties and water chemistry carried out from August to October 1994 documented that the spring water is fresh (EC: 341–367 µS/cm; TDS: 200–250 mg/L), slightly alkaline (pH 7.5–7.6), moderately hard (total



Text-fig. 1. Location of karst springs: Blue Springs (1), Goryczkowe Vaucluse Spring (2), Zygmunt Spring (3).

hardness: 182–194 mg $CaCO_3$/L), of normal temperature (8.7–12.0°C), with transitional redox conditions (Eh: 125–240 mV), and of the HCO_3-Ca-Mg hydrochemical type (Table 1) (Małecka and Małecki 1998).

Monitoring conducted by the Regional Inspectorate for Environmental Protection as part of the national groundwater monitoring network from 2004 to 2007 included four boreholes in the vicinity of

Component	Ca	Mg	Na	HCO_3	SO_4	Cl	NO_3	SiO_2
	[mg/L]							
Blue Springs	55–65	7–10	3–5	170–210	15–25	5–8	0	10–13
Cretaceous Aquifer	16–31	2–3	2–4	43–116	2–9	2–5	3–26	10
Jurassic Aquifer	53–96	5–12	2–6	228–287	8–48	3–16	0–27	9

Table 1. Chemical composition of the waters of the Blue Springs (08–10.1994) and groundwater from the Cretaceous and Jurassic aquifers (2004–2007).

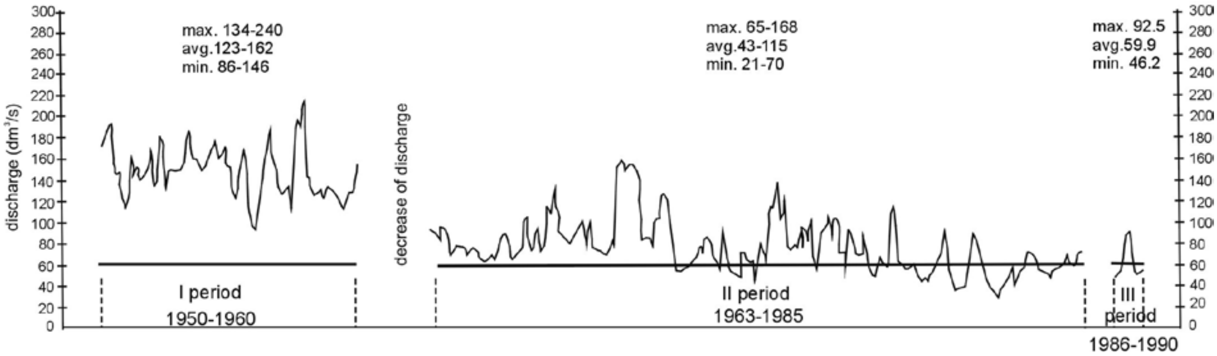
Blue Springs. These data reflect the water chemistry of both the Cretaceous and Jurassic aquifer levels (Koślacz *et al.* 2010). The water from these aquifers is characterized by the following parameters: Cretaceous aquifer: fresh water (EC 122–167 µS/cm), weakly acidic to alkaline (pH 6.85–7.77), with a temperature range of 8.8–12.8°C, of the HCO_3-Ca type (Table 1); Jurassic aquifer: fresh water (EC 339–615 µS/cm), weakly acidic to alkaline (pH 6.99–7.97), with a temperature range of 8.6–12.9°C, of the HCO_3-Ca type (Table 1) (Koślacz *et al.* 2010).

Spring hydrogeological conditions. The characteristic karst features in the catchment area of the Blue Springs include a series of intersecting tectonic dislocations, the karst sinkhole known as "Przepaść," and the underground flow of the stream to the springs, as well as karstic sinkholes. The primary source of recharge for the springs is the fractured and karstified thick-bedded limestones, in a belt about 600 m wide, extending from the south in the NW-SE direction (Text-fig. 1). The spring discharge is dependent on rainfall and water levels in the Pilica River. The recharge of the Blue Springs occurs through the infiltration of rainfall into the Quaternary sands and gravels, which lie directly over the Jurassic limestones or directly into them in areas where these formations outcrop at the surface. The unit infiltration rate reaches 5.1 l/s·km² (Małecka and Małecki 1998). The recharge zone is located in the area bordering the Pilica Valley to the southeast, where a series of karst sinkholes occur. According to Koślacz *et al.* (2010), the recharge zone covers an area of 10.15 km². The unit discharge rate at the Brzóstówka monitoring well (located 0.5 km away) is above 400 m³/h·m, indicating an intense water inflow into the fractured-karst system. A dye introduced into the "Przepaść" sinkhole appeared in the springs after 5 days, which indicates a rapid water flow through the fractured-karst system, estimated theoretically at around 0.007 m/s. The conceptual model of groundwater circulation indicates that, in most of the recharge area of the Blue Springs, there is a shared groundwater table (Q-Cr-J), constituting a single hydrologically connected water circulation system (Małecka and Małecki 1998).

*Decline in spring discharge related to plans for municipal water supply***.** Initially, the waters of the Blue Springs flowed into the Pilica River at Brzóstówka (currently the protective ditch). The first intervention in the hydrological system of the springs was the construction of a tunnel to direct the water for powering a mill in Nowy Ludwików. After 1936, a dam was built, artificial channels were dug, and the water discharge was impounded at the outflow in Nowy Ludwików. In 1957, a concrete retaining wall was built along the western shore of the floodplain to protect the spring from periodic inflows of Pilica River water. At the beginning of the last century, research began to assess the potential use of these waters for the water supply of Łódź and Tomaszów Mazowiecki. In 1903, a well was drilled where a high unit discharge of 190 m³/h/1m² was achieved, with a stabilized water table of 1.37 m above the reference point, i.e., at an elevation of 156.22 m, which is more than 1.7 m higher than the current level. In 1923, Lindley developed a project for the water supply of Łódź, including the use of waters from the Blue Springs (Małecka and Małecki 1998). In 1938, wells were drilled on the left side of the Pilica River, and in 1940, a well 30 meters deep was drilled near the Blue Springs. Between 1950 and 1953, 31 operational and observation wells were drilled along a 70-meter section of the valley, on the right bank of the Pilica River in Brzóstówka. To confirm the exploitation resources, a pumping test was conducted in 1961. With a discharge rate of 1233.5 m³/h, a rapid decline in the spring flow was observed. The water level at the spillway in Nowy Ludwików dropped by 31.2 cm (Turek and Gaik 1986). As a result, only two wells ("C" and "F") were put into operation for the city of Tomaszów Mazowiecki as emergency wells.

Analysis of the discharge rates of the Blue Springs for three periods (1951–1960, 1963–1985, and 1986–1990) reveals a clear trend of declining spring discharge (Text-fig. 2).

The cause of the regression in spring discharge was the disruption of the hydrodynamic equilibrium caused by the aforementioned collective pumping at the Brzóstówka intake in 1961, with a discharge several times higher than the average annual dis-



Text-fig. 2. Trend of average monthly discharge of the Blue Springs compared to the average from the period 1986–1990.

charge of the Blue Springs. The spring discharge was also influenced by the lowering of the local erosion base during hydroengineering works associated with the construction of a weir on the Pilica River. This led to the impoundment of water in reservoirs and the activation of leaks on the outer side of their embankments, as well as the appearance of discharges between the reserve and the natural course of the Pilica River. The increase in filtration resistance in the springs was also influenced by the accumulation of muds and organic substances in the limnocrene, reaching a thickness of 1.5–2 meters.

To restore the hydrostatic pressure which conditions the discharge of the Blue Springs, in 1994, a cleaning and dredging process of the water reservoirs was initiated. A dam was constructed in the old riverbed of the Pilica River. The eroded banks of the reservoirs were regulated and reinforced, channels were deepened, the spring basins were dredged, and the entire reservoir was deepened and regulated, including the protective ditch. A constant difference in level was maintained between the reservoirs and the surface water levels of the Pilica. Ongoing monitoring documented the activation of the springs, the halting of decay processes in the reserve's reservoirs, and an increase in the average discharge to above 60 l/s. However, the discharge which had been documented by Lindley – 220 l/s in 1923 – was not achieved, even under maximum conditions (Małecka and Małecki 1998).

The impoundment of water and technical interventions within the spring areas also prevented the formation of travertines (Kurowski *et al.* 2008, cited in Koślacz *et al.* 2010).

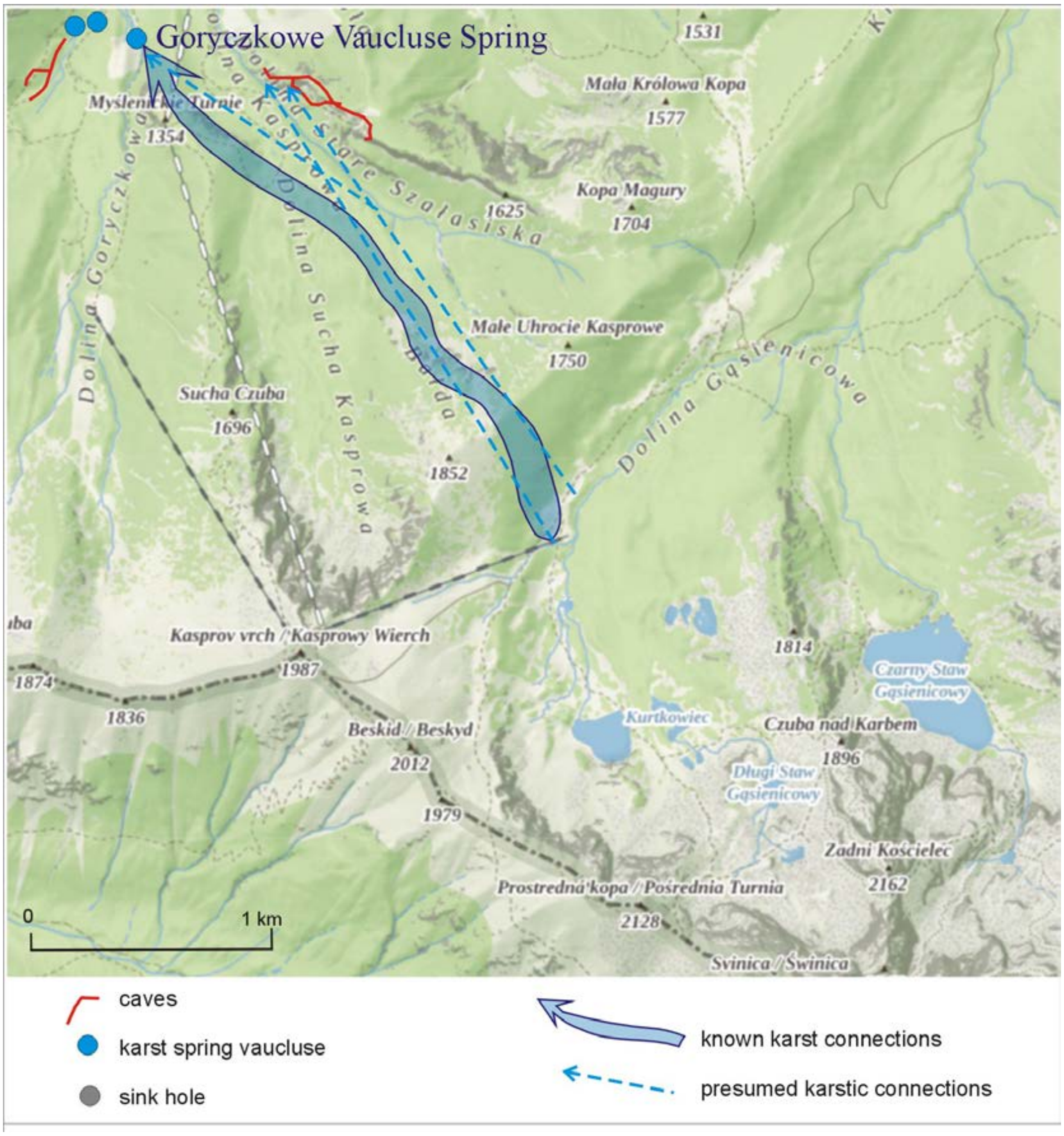
The threats to the recharge area of the Blue Springs include internal threats such as tourism pressure, the development of the immediate surroundings (including the village of Wąwół within the reserve), forestry, hydrotechnical and drainage structures (e.g., blocking discharge at Nowy Ludwików); external threats such as urban agglomeration (Tomaszów Mazowiecki), groundwater extraction (two groundwater intakes), water and sewage management (two sewage treatment plants) and petrol stations in Tomaszów Mazowiecki, industrial plants in Wąwół, as well as wet and dry deposition, and the hydrotechnical development of the Pilica River (Koślacz *et al.* 2010; Gałka and Wilk 2015).

Goryczkowe Vaucluse Spring

Hydrogeological Characteristics. Goryczkowe Vaucluse Spring is a perennial, ascending, fault-controlled, fissure-karst spring of external circulation, located at an elevation of 1190 m a.s.l. It drains Triassic deposits of the High Tatra succession, which consists of light reef limestones, massive organogenic limestones, red brecciated limestones, hornstone limestones in beds, conglomerates, clay shales, and quartz sandstones (Text-fig. 1).

The discharge regime of the karst spring, studied between 1980 and 2019, is as follows: discharge (minimum, average, maximum) was: 166/800/>1000 (L/s) (based on stationary observations – daily measurements of water table levels and the consumptive curve). The base flow (QRO) between 1980 and 2001 ranged from 201 to 740 L/s, with an average of 310 L/s. The variability index classifies the spring as variable and highly variable (Barczyk 2003a, 2008). The maximum discharge of the spring is estimated to be 40 m³/s. The spring occurs within the main groundwater reservoir of Zakopane (No. 441), a fissure-karst type, composed of formations ranging from Paleogene to Triassic, with an estimated available resource module $Q_{(disp.)}$ = 66.2 m³/d.km².

Discharge from Goryczkowe Vaucluse Spring



Text-fig. 3. Location of karst flow paths within the Goryczkowe Vaucluse Spring system.

was monitored from the 1980s until July 1997 by a stream gauge installed at the edge of the Goryczkowy Stream, 50 m below the main spring outflow. The 1997 flood destroyed the gauge. From 1998 to 2005, the outflow was monitored by an automatic limnimeter, located 5 m below the spring outflow (Barczyk 2008), and since 2009, a limnimeter operated by the staff of the Tatra National Park.

Studies of the physicochemical properties and chemistry of groundwater conducted continuously between 1960 and 2019 document ultra-soft waters (total mineralization around 60 mg/L), as the recharge area primarily encompasses regions of crystalline rocks. Electrical conductivity (PEW) values measured between 1999 and 2003 ranged seasonally from 130 to 250 µS/cm, never exceeding 150 µS/cm. These waters are weakly alkaline (pH 7–8.3), soft to moderately hard (TH <100–200 $mgCaCO_3$/L), thermally cool / normal with temperatures of 4.1–5.4°C, and are of the HCO_3-Ca type. The average proportion of major ions was as follows – among anions: HCO_3 76%, SO_4 14%, Cl 10%; among cations: Ca 75%, Mg 19%, Na+K 6%. With a carbonate aggressiveness index (Sic) of -1.19, the rate of chemical denudation from the recharging karst waters is approximately 90 m^3/km^2 per year (Barczyk 2008). Quantitative changes are regularly observed and are associated with the hydrological cycle of water circulation within the spring systems.

Spring Hydrogeological Conditions. The recharge area of the Goryczkowe Vaucluse Spring extends beyond the surface watershed of the Goryczkowy Stream. It encompasses the karst massif of Myślenickie Turnie, alluvial-moraine sediments filling the valley, and karst systems reaching into the basin of the Sucha Woda Stream. Karst connections between the spring and the Sucha Woda catchment have been confirmed by numerous dye-tracing experiments (since 1964), and water travel times within the karst system range from 13 to 24 hours. Based on a distance of 2.75 km and an elevation difference of approximately 435 m, assuming a hypothetical straight flow path, the estimated flow velocity ranges from 0.033 to 0.058 m/s (Barczyk 2003b, 2004; Małecki 2007). At high water levels in the massif, additional circulation pathways are activated, connecting the spring system to the Kasprowa Niżna Cave system (Barczyk 2008) (Text-fig. 3).

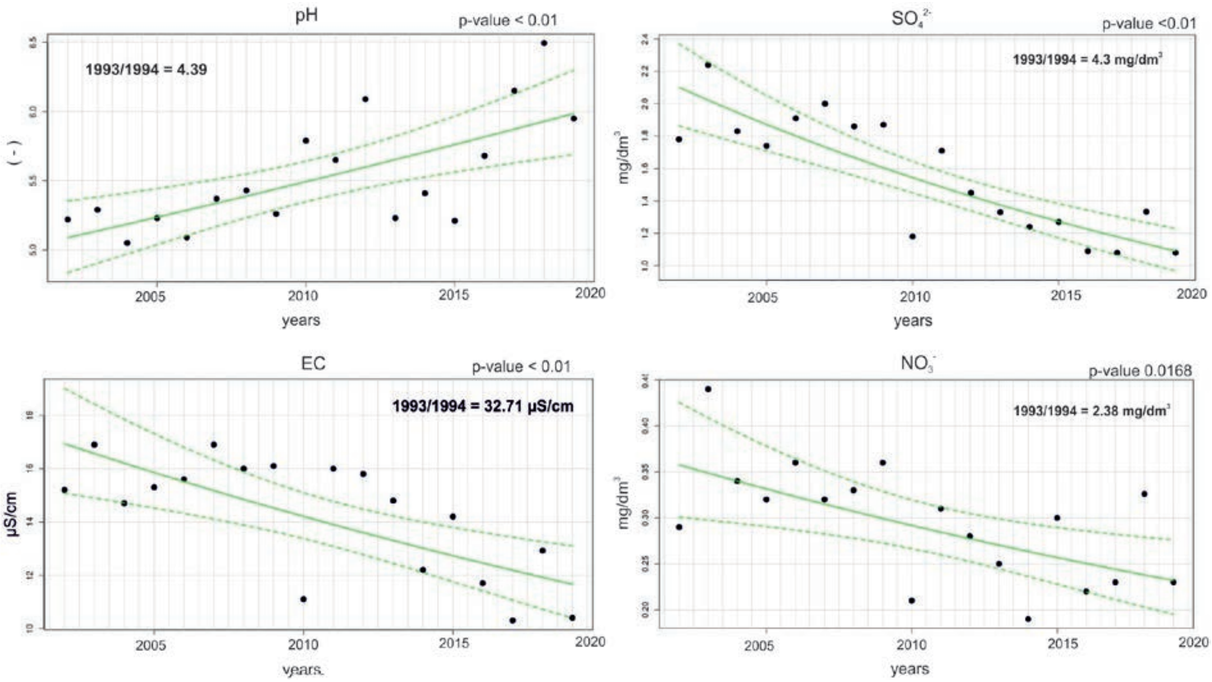
According to stable isotope studies ($\delta^{18}O$ and $\delta^{2}H$), the elevation of the recharge area is estimated at 1581 m a.s.l. (Zuber *et al.* 2008), which corresponds with the elevation of the main swallow zone located below Litworowy Pond in the Gąsienicowa Valley (approx. 1600 m a.s.l.) (Barczyk 2008). The average residence time of water in the porous and fissured systems is estimated to be 3–5 years (Zuber *et al.* 2008). The estimated volume of water stored in the local and regional reservoirs supplying the Goryczkowe Vaucluse Spring, calculated using Mangin's formula, is approx. 2.1×10^6 m³ and 1.2×10^7 m³, respectively (Barczyk 2008).

Observations of water levels and periodic flow volume measurements, conducted since 1977 (Barczyk 2008), have shown that the fluctuation patterns of the Goryczkowe Vaucluse Spring discharge and the surface water flow display a similar trend, closely resembling the fluctuation rhythm of discharge and flow observed in other Tatra karst springs. Low and medium water levels are the best documented. During high flow conditions, both the spring and the Goryczkowy stream carry vast volumes of water with such turbulence that direct flow measurements become impossible. In periods of high and very high flows, the discharge of the spring can only be estimated by interpreting the recession curve.

Passive Reception of Atmospheric Pollution. The chemical composition of precipitation plays a significant role in influencing aquatic ecosystems in the Tatra Mountains, including biocenoses and the exposure of karstifying rocks. The chemistry of precipitation in the Tatras is predominantly controlled by continental sources. Since 1993, temporal changes in its composition have largely resulted from anthropogenic processes, including those associated with distant pollution sources (Barczyk *et al.* 2002; Małecki *et al.* 2022). The passive reception of atmospheric pollutants by the Tatra hydrosphere is documented in the studies of Małecki *et al.* (2022). Rainwater samples were collected at two observation sites: in Hala Gąsienicowa (1520 m a.s.l.) during 1993–1994, and on Kasprowy Wierch (1991 m a.s.l.) from 2002 to 2019. The chemical composition of precipitation was analyzed in the laboratories of the Polish Geological Institute in Warsaw, the University of Warsaw, and the Chief Inspectorate of Environmental Protection. Trends in water chemistry changes were analyzed using GWSDAT software. During 1993–1994, pH values ranged from 3.4 to 6.42 (average 4.39), while in the period from 2002 to 2019, pH increased from 5.22 to 5.95. Electrical conductivity (EC) decreased from 4.2–193 µS/cm (average 32.71 µS/cm) in 1993–1994 to 15.2 µS/cm in 2002 and 10.4 µS/cm in 2019. The observed trends indicate an improvement in atmospheric air quality, which is reflected in the chemical composition of rainwater and in the concentrations of sulfates and nitrates between 1993–1994 and 2002–2019 (Małecki *et al.* 2022) (Text-fig. 4).

Annual hydrogen ion (H^+) loads have gradually decreased from 30 kg/km²/year in 1993–1994 to 17 kg/km²/year in 2004, and further down to 2 kg/km²/year in 2019. This trend is reflected in the measured pH of rainwater in the Tatra Mountains, which increased from pH = 4.39 in 1993 to pH = 5.95 in 2019.

For precipitation sampled on Kasprowy Wierch during 2002–2019, the acid potential (AP) showed a decreasing trend from above 0.016 to 0.012, while the total neutralization factor (NF) for cations (NH_4^+, Ca^{2+}, Na^+, K^+, and Mg^{2+}) statistically increased from 1.7 to 2.4. The ammonium availability index (AAI) also rose from below 0.5 to over 0.65. However, this still indicates that sulfates and nitrates are not fully neutralized by ammonium ions (AAI < 1) (Małecki *et al.* 2022). In other regions of Poland the chemical composition of precipitation depends on the state of the atmospheric air and varies depending on the location and season (https://powietrze.gios.gov.pl/pjp/maps/modeling). The observed trends in precipitation chemistry in the Tatra Mts. result from reduced emissions of gases and particulates in Poland and neighboring countries. Air quality improvement has also been supported by the



Text-fig. 4. Values of pH, electric conductivity (EC), concentrations of sulfates and nitrates in rainwater in Tatra Mts (Małecki *et al.* 2022).

development of geothermal energy in the Podhale region. Until 1993, the heating installation operated on an experimental scale, based on a production well (Bańska IG-1) and an injection well (Biały Dunajec PAN-1) as part of the Experimental Geothermal Plant of the Polish Academy of Sciences in Bańska-Biały Dunajec. In 1994, Geotermia Podhalańska S.A. was established, followed by the creation of PEC Geotermia Podhalańska S.A. in 1998. In 2001, two additional wells were commissioned: Bańska PGP-1 (production) and Biały Dunajec PGP-2 (injection) (Górecki 2006). As a result, air quality in the Zakopane area has significantly improved, as confirmed by data from 2010–2019, particularly during the winter season (Table 2) (Anioł *et al.* 2022). Unfortunately, in some regions of Poland, coal burning during winter remains widespread, which is confirmed by carbon isotope analyses of aerosols in the Kraków area (Zimnoch *et al.* 2020).

Zygmunt Spring

Hydrogeological characteristics. Zygmunt Spring is a permanent, hillside spring. It is a descending-type rheocrene, classified as a fissure-karst spring, situated at an elevation of 296 m a.s.l. It is located within the drainage zone of the Upper Jurassic aquifer, composed mainly of limestone and, subordinately, marl (Text-fig. 1).

The Zygmunt Spring represents a large spring zone with multiple outflows associated with intersecting tectonic dislocations. A niche has developed on the slope, covering an area of approximately 600 m², from which a dozen or so springs emerge. Strong headward erosion is occurring. The discharge regime of the karst spring, studied over the period 1951–2009, is as follows: discharge (minimum, average, maximum) was 15 / 62 / 118 L/s, respectively; the discharge variability index $R = Q_{max}/Q_{min}$ ranges from 2 to 8. The spring's discharge corresponds with the high renewable resource module of the Częstochowa (E) Major Groundwater Body (No. 326), within

Parametr	Seasons	2010	2019
PM_{10}	warm season	24.20	22.64
	cold season	66.06	32.04
NOx	warm season	12.93	14.51
	cold season	28.25	21.90
SO_2	warm season	2.96	7.26
	cold season	19.54	9.26
L PM_{10}>50	days	85	28
L PM_{10}>100	days	36	1

Table 2. Air pollutant concentrations (µg/m³) at the monitoring station in Zakopane (49.2935 N, 19.9600 E) in the years 2010–2019. The number of days with exceedances of the limit value PM_{10} (L > 50) and (L > 100) in Zakopane. Explanation: The number of days with exceedances of the limit value PM_{10} (L > 50) and (L > 100) in Zakopane.

which the spring is located, amounting to $Q_{(renewable)}$ = 410 m³/day·km² (Różkowski 2009).

Physico-chemical Properties and Chemistry of Groundwater. Periodic studies of the physico-chemical properties and groundwater chemistry conducted between 1981 and 2022 confirm that the waters are fresh (SEC 360–479 µS/cm), slightly alkaline (pH 7.0–7.9), moderately hard (TH 172–210 mgCaCO$_3$/L), thermally temperate with temperatures ranging from 8.7 to 9.6°C. The environment is weakly oxidizing (Eh 385–563 mV; O$_2$ 7.8–12.1 mg/L). Zygmunt Spring waters are of the HCO$_3$-Ca type with the following chemical composition (mg/L): TDS 187–250; Ca 68–82; Mg 0.4–4; Na 3–6; K 0.3–2.5; HCO$_3$ 177–214; SO$_4$ 11–19; Cl 3–15; NO$_3$ 2–22; SiO$_2$ 5–7 (based on data from 1981 and 2009–2011).

Hydrogeological Conditions of Spring Functioning. The Wiercica catchment area within the Upper Jurassic aquifer covers 187 km². Karst features of the basin include both perennial and intermittent springs, extensive spring zones, sinkholes, fault zones with widths of 200–1300 m and displacements of 20–50 m, and numerous depressions. The Upper Jurassic limestone massif is characterized by an average effective porosity of 9.3%, fissure porosity ranging from 0.12–2.25%, and conduit porosity from a fraction up to several percent. Average flow velocities in the Jurassic limestones reach several thousand meters per year, while in micro-hydraulic pore systems, they range from a few meters to several tens of meters annually. Interpretation of tritium concentrations in spring waters within the Wiercica basin indicates that the mean groundwater residence time in the aquifer system (including fissure, karst, and porous flow) varies between 45 and 100 years. According to hydrological modelling studies, groundwater contributes approximately 85% to the total runoff in the Wiercica catchment (Różkowski 1990). Since 1975, the Polish Geological Institute has been conducting hydrogeological balance studies in this 187 km² carbonate area, designated as a research catchment.

Decline in Biotic Values and Water Quality Due to Tourism and Fish Farming. Zygmunt Spring is the headwater of the Wiercica River. Human interference has modified the environmental conditions and hydrological regime of the river since the 19th century. Zygmunt Spring (named in honor of the Polish poet Zygmunt Krasiński), together with the adjacent Elżbieta Spring, supplies water to fish ponds located 300 meters downstream. These ponds were estab-

Text-fig. 5. Contemporary Trout House (photo Kokoszka).

lished by Count Raczyński in 1881 and became the largest trout farm in continental Europe. Initially consisting of 22 ponds (expanded to 46 ponds by the early 20th century), the farm covered an area of 13.2 ha, with ponds up to 4 m deep, and included a hatchery building. In 1881, rainbow trout were imported from California. The farm raised three species of trout, Atlantic salmon, eel, and pikeperch. Trout roe was cultivated and exported across Europe. The trout farm remains operational to this day (Text-fig. 5).

Zygmunt Spring – Biodiversity and Environmental Assessment. The spring is characterized by moderate biodiversity, supported by a diverse mineral composition of the sediments in the spring niche: calcite (65%), quartz (20%), and subordinate amounts of dolomite (5%) and illite (up to 3%). Within the spring niche, 11 plant species were recorded (including species of the *Montio-cardaminetea* class, characteristic of spring habitats, such as *Cardamine amara*), while an additional 10 species were identified on the margins of the spring. The Shannon diversity index was 0.63 and 0.54, respectively.

A total of 19 diatom species were found on stones and mosses, including aerophilic taxa associated with desiccation (*Diadesmis contenta*), as well as representatives of five invertebrate orders. Research conducted by Dumnicka (2009) confirmed the presence of the groundwater amphipod *Niphargus tatrensis*, a species associated with subterranean aquatic habitats (Okoń *et al.* 2020).

Direct Threats to the Spring and Its Biotic Elements. The spring is under direct threat from several factors. A regional road runs approximately 15 meters above the site, facilitating heavy tourist traffic and increasing the risk of water contamination. Additional stressors include water abstraction for drinking purposes, unregulated wastewater management, excessive shading, and the potential for the spring to dry out during hydrological droughts. Due to intense tourist activity and ongoing climate change, the spring hosts a low abundance of benthic fauna species. Dominant invertebrates include the flatworm *Dugesia gonocephala*, the freshwater amphipod *Gammarus fossarum*, and various caddisflies such as *Drusus trifidus*, *Odontocerum albicorne*, and species from the families *Geridae* and *Odontoceridae*. Flies from the families *Limoniidae* and *Stratiomyidae* are also present. Field studies by Okoń (2012) did not confirm the continued presence of the alpine flatworm *Crenobia alpina* (previously reported by Poliński in 1926, cited in Okoń 2012), which may have gone extinct during a severe low-water event in 1988. Similarly, *Niphargus tatrensis* and the Carpathian spring snail (*Bythinella austriaca*) were not observed, despite earlier records (Skalska and Skalski 1992, cited in Okoń 2012). An attempt in 2001 to transplant the endemic *Cochlearia polonica* from the Centuria spring niche to Zygmunt Spring was unsuccessful; the species has not been recorded at Zygmunt Spring since 2006 (Okoń 2012).

Hydrobiological Status Assessment. The hydrobiological status of Zygmunt Spring was evaluated by Okoń (2012), who analyzed environmental factors influencing habitat heterogeneity and catalogued flora and fauna species that indicate the natural condition of spring ecosystems (Table 3). The assessment considered features contributing to biodiversity. Zygmunt Spring received a relatively high biodiversity score of 14 out of 26 points when compared with several representative springs in the Kraków-Częstochowa Upland region (Okoń 2012; Okoń and Różkowski 2013).

Feature/ species	Niche size	Productivity	Subsurface	Thermal conditions – water temperature amplitude	pH	NO_3 water concentration	Sun exposure
Rank	1	1	1	1	1	1	0
Feature/ species	Protected area	Anthropogenic changes	Anthropogenic threat	*Cratoneuron filicinum*	*Pellia epiphylla*	*Cochlearia polonica*	*Veronica becca bunga*
Rank	1	1	0	1	0	0	1
Feature/ species	*Berula erecta*	*Nasturcium officinale*	*Mentha longifolia*	*Crenobia alpina*	*Bythinella austriaca*	*Potamophylas nigricornis*	*Plectrocnemia conspersa*
Rank	1	0	0	0	0	0	0
Feature/ species	*Drusus trifidus*	*Odonto cerum albicorne*	*Phagocata* sp.	Population size	Species abundance fauna	Total score	
Rank	1	1	0	1	0	14	

Table 3. Summary of Environmental Features Influencing the Natural Habitat Diversity of Springs and Indicator Species Reflecting the Natural Environmental Status of Zygmunt Spring: 1 – Presence of the species or a beneficial effect on environmental diversity; 0 – Absence of the species and a less beneficial effect on environmental diversity.

Finally, for Zygmunt Spring, organic pollution indices were determined: IPS (Specific Pollution Sensitivity Index; Cemagref, 1982) and TDI (Trophic Diatom Index; Kelly, Whitton, 1995), which indicate trophic conditions and the proportion of species sensitive to pollution (%PT – pollution taxa). The IPS index was 14.5, which corresponds to moderately polluted waters (mesosaprobic waters). The TDI index was 79.6, which corresponds to waters of poor quality (eutrophication) (Okoń 2012; Okoń *et al.* 2020). Tourist exploration of the spring poses a bacteriological risk to the water, as documented by studies conducted by Dąbrowska and Ruman (2025) in November 2023 and May 2024. The total number of bacteria cultured at 22°C for 72 hours was over 300 CFU/ml, exceeding the WHO standard of 100. The total number of bacteria cultured at 36°C for 48 hours ranged from 12 to 13 CFU/ml (permissible value 20). In May 2024, Enterococci were detected in the water at a concentration of 14 CFU/100 ml, which may indicate contamination by human fecal bacteria (permissible value 0).

SWOT Analysis

A common feature of all the analyzed springs (Blue Springs, Goryczkowe Vaucluse Spring, and Zygmunt Spring) is their karstic nature, the very high spring yields, and their aesthetic values, which allow them to be classified as natural heritage sites and included in the MIKAS or NIKAS databases. A distinguishing element among these springs is the type of anthropogenic pressure exerted on them. In the case of Blue Springs, anthropogenic pressure is manifested through modifications to the hydrological network and changes in circulation conditions, due to attempts to extract groundwater for drinking water supply to the city of Łódź, which led to a decrease in the spring's yield from 220 L/s to 77 L/s and degradation of travertine deposits. For Goryczkowe Vaucluse Spring, located in the Tatra National Park, anthropogenic influence occurs indirectly through the migration of atmospheric pollutants from industrialized regions outside the park. The hydrosphere of the Tatra Mountains acts as a passive receiver of pollutants, which has undergone significant changes over the years, but has been gradually improving in recent years, partly due to the development of geothermal energy in the Podhale region.

The analysis of the state of atmospheric air from stations located near the analyzed sources shows that in 2023, in the case of Blue Springs and Zygmunt spring, the greatest threat is suspended dust (PM_{10} and $PM_{2.5}$) associated with nearby urban agglomerations (https://powietrze.gios.gov.pl/pjp/maps/modeling). Due to the specificity of transport of these pollutants in the area of Goryczkowe Vaucluse Spring, this type of pollution is not revealed. In the case of gaseous pollutants (NO_2 and SO_4), the average annual values are generally low, while they are periodically exceeded in all analyzed regions, and SO_4 especially in the winter.

In the case of Zygmunt Spring, the type of anthropogenic pressure is intensive tourist exploitation, which, despite the protection provided by the nature reserve, has led to a reduction in biodiversity, manifested by a low number of benthic fauna species, unsuccessful reintroduction of the endemic *Cochlearia polonica*, poor water quality (eutrophication), and poor bacteriological water conditions.

The tourist load is also problematic in Blue Springs, due to the proximity of large cities (e.g. from Warsaw it is approx. 130 km), which means that this place is often

Strenghts	Weaknesses
– Aesthetic values – Natural, cultural, and biological heritage – Areas protected under Natura 2000 – Pristine nature (native and unique species, with no introduced plants in many areas) – Inclusion in the MIKAS list (Goryczkowe Vaucluse Spring and Zygmunt Spring) or the NIKAS list (Blue Springs)	– Limited possibilities/quantities for economic use of water – Limited possibilities for land development for purposes other than tourism
Opportunities	**Threats**
– Development of environmental education – Development of tourism in the region – Development of broadly understood ecological methods to protect the environment and water resources (e.g., water-saving technologies) – Popularization of karst springs in the media	– Air pollution due to the migration of contaminants from industrialized areas – Damage to unique vegetation (movement beyond designated tourist trails and roads) – Increased water demand (tourism development) – Increased wastewater and waste generation (tourism development) – Environmental contamination, including the recharge zones of springs (littering in areas not designated for waste disposal)

Table 4. SWOT Analysis.

visited. It is difficult to determine the scale of tourist traffic, because the reserve is open all year round at any time and entry is free. In the case of Goryczkowe Vaucluse Spring, the tourist aspect is negligible, because it is located outside the mountain trail.

Despite the pro-ecological actions undertaken, environmental changes have been observed in the vicinity of all the studied springs. A good approach to continue the most rational management of water resources and to assess and balance the opportunities and threats is to conduct a SWOT analysis (Table 4).

The location of the springs in protected areas, such as within parks or nature reserves, provides only partial protection, as pollutants can migrate through the air over significant distances. However, such a location offers protection in the form of limited potential and quantities of water usage, as well as restricted land development, typically associated with sightseeing and tourism. Effective protection of spring zones would be possible through the establishment of direct protection zones around the springs, but the studied springs do not qualify for such a zone, as they are not water sources for drinking purposes. In this context, there is a clear need for environmental education, both regarding the springs as objects of visitation and in terms of the infrastructure that will serve tourism purposes. The associated risks, such as the increased demand for water, the generation of wastewater and domestic waste, and the failure to adhere to regulations in designated protected areas (e.g., damage to unique vegetation), must be considered.

SUMMARY AND CONCLUSIONS

- Three unique springs were analyzed, classified on the MIKAS list (Goryczkowe Vaucluse Spring and Zygmunt Spring) or NIKAS list (Blue Springs), which were selected from 14 springs from karst areas in Poland, draining formations composed of carbonate, silicate, and sulfate rocks. The selection criterion for this analysis included: the karst nature of the aquifer, the occurrence of the springs in different regions of the country, the highest source outputs in the country, long-term monitoring studies, documentation of the anthropogenic impact on the environment at the spring outflow site, and the diversity of anthropogenic factors.
- The Blue Springs are the largest karst spring in the Polish Lowlands. They are protected within the "Blue Springs" nature reserve, but do not have a direct protection zone. The location on the floodplain terrace of the Pilica River led to technical works in the 19th century, which modified the limnocrene, including the digging of channels (e.g., directing water to operate a mill), the construction of a dam, and the building of a retaining wall. An attempt to supply water to the residents of Łódź (hydrogeological drilling studies in the 1960s) resulted in a more than threefold reduction in the spring's output, despite later complex engineering efforts aimed at its restoration. At the same time, excessive impounding of the limnocrene halted the deposition of travertine.
- 3) The Goryczkowe Vaucluse Spring is the largest karst spring in Poland, with a maximum estimated output of 40 m^3/s, monitored for 40 years, draining a complex fracture-karst system with a rapid response to "Aliou"-type recharge. It is protected within the Tatra National Park, but does not have a direct protection zone, and the waters of the Goryczkowy stream below the spring are used for drinking purposes. A manifestation of anthropogenic pressure in the Tatras is the passive reception of atmospheric pollutants in the form of dry and wet deposition. Observed trends in the chemistry of precipitation waters are the result of reduced emissions of gases and dust in Poland and Slovakia since the 1990s, including the establishment of the Podhale Geothermal Company in 1994. For precipitation waters from Kasprowy Wierch, the acid potential (AP) showed a decreasing trend from 2002 to 2019, and the total neutralization factor (NF) for cations increased statistically, but the ammonium ion availability index (AAI) of 0.65 indicates that sulfates and nitrates are not completely neutralized by ammonium ions.
- The Zygmunt Spring, located in the largest karst area in Poland, the Silesian-Cracow Upland, with unique landscape values, supplied the largest trout farm in continental Europe in the 19th century. Despite being protected within the "Parkowe" nature reserve (since 1957), but without a direct protection zone, it is exposed to intensive tourism, which has led to the degradation of the biological environment, particularly the impoverishment of benthic fauna, the failed reintroduction of the endemic *Cochlearia polonica*, and a poor organic pollution index (TDI), indicating poor water quality. The tourism exploration of the spring poses a bacteriological threat to the water used by the population for drinking purposes.
- Human interference in spring zones, which has been different in each of the three discussed cases, has permanently changed the spring regime and

the accompanying biosphere, and contributed to the anthropogenization of the surrounding environment. The changes made in the past are so deeply ingrained that a return to the original state is not possible.

- A valuable and significant initiative was the creation of a database of springs of global significance (MIKAS and NIKAS), which not only inventories important areas in terms of water resources but also in a broader environmental context. It is also a valuable guideline in terms of the possibilities and limitations of land management in the vicinity of the springs, as well as the implementation of sustainable tourism.

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