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Dependence of the karstic waters in the Tatra Mts. on changing atmospheric conditions

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ABSTRACT:

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The paper presents data obtained from continuous limnimetric observations of the Tatra vaucluse type springs carried out in the interval 1999-2000. The comparison of 24-hour changes of the water level for particular vaucluse springs and the characteristic levels indicate a distinct correlation of the spring reaction to atmospheric changes, which is confirmed by comparison of correlation coefficients. Analysis of hydrograms from particular vaucluse springs during spring thawing, and their distinct bipartition, allows the determination of the filling times of local groundwater basins (over 7 days). Interpretation of changes in water levels for the vaucluse springs during a rainfall episode that caused the maximum filling of the massif, reveals 6-8 hours as the time of rainfall/water level reaction for the Tatra vaucluse type springs.

Key words: Tatra Mountains, Karstic waters, Vaucluse type springs.

INTRODUCTION

Vaucluse springs, transporting water from fissure-karst systems, result from karst development in the area. At the same time, they are the main source of information on the hydrography of the investigated karst area. In the Polish Tatras, karst processes develop in relatively restricted areas of limestone and dolomite in regions of strongly folded sedimentary rocks. Within the overthrust tectonic units (the Hightatric and Subtatric successions), the karstifying calcareous deposits are separated by non-permeable rocks. In the Hightatric succession, the most intense development of karst is characteristic of the Middle Triassic limestones and dolomites, as well as the Jurassic and Cretaceous limestones. In the Subtatric succession, karst processes take place within the Middle and Upper Triassic limestones and dolomites (GŁAZEK 1995). The main karst springs of the Tatra Mountains appear in the contact zones between the karstifying deposits and the poorly or non-soluble rocks. Continuous monitoring of groundwaters and surface waters in the Tatra Mountains in Poland has been carried out for a long time. In the mid-1970s, the team under Prof. D. MAŁECKA organized a monitoring network, with water marks along the main Tatra streams right to their outlets from the massif, and with observation points of the largest springs and vaucluse springs. Readings from water marks were collected several times each month by the observers (usually Tatra National Park employees). With minor changes, the network is still in operation. Many papers on the hydrology of the Tatras were based on the interpretation of data collected from the network (MAŁECKA 1984, 1985, 1993, 1996, 1997, MAŁECKA & HUMNICKI 1989, HUMNICKI 1992).

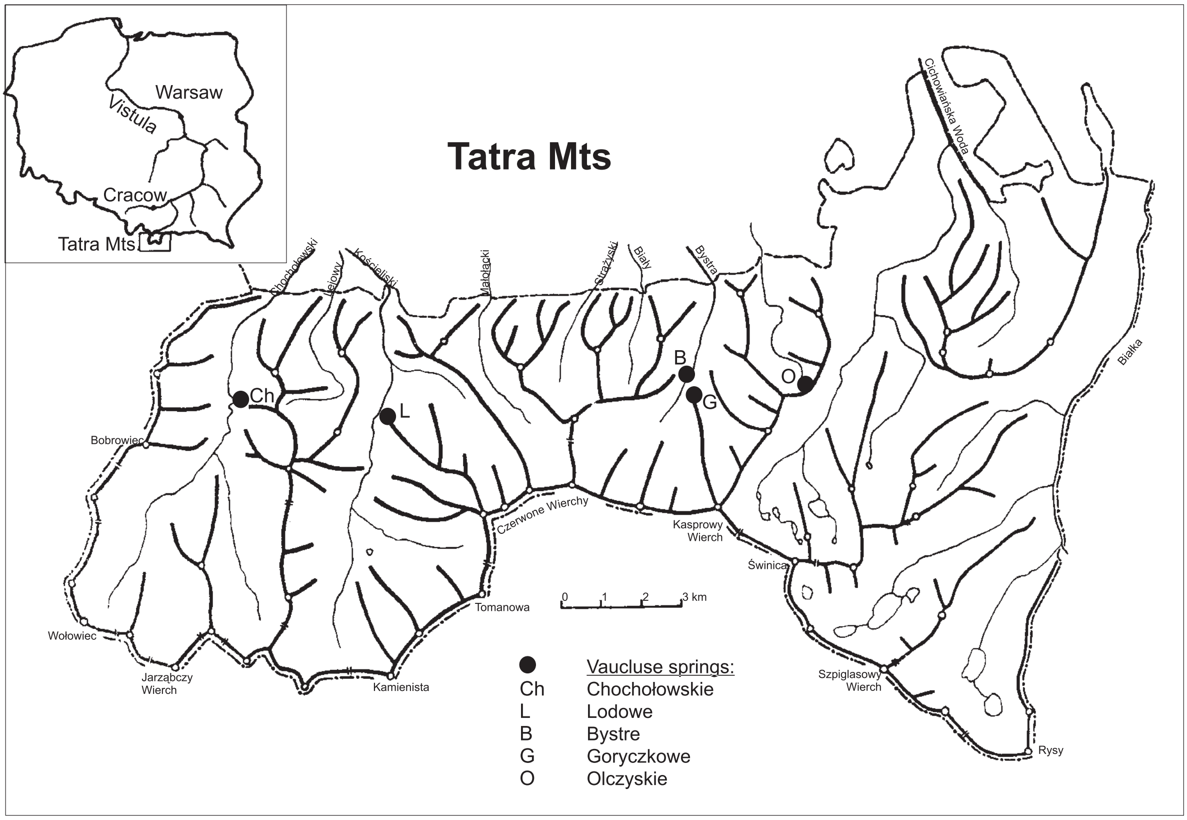


Fig. 1. Schematic location of the Tatra vaucluse springs

In 1998 the Committee for Scientific Research approved a three-year research project entitled: "Determination of retention abilities and the dynamics of denudation in the karst areas of the Polish Tatra Mountains based on stationary investigations of vaucluse springs". In accordance with this project, between November and December 1998 automatic continuous water level recorders were installed in selected vaucluse type springs (Text-fig.1). These devices are supplied with capacity probes, in which water level changes cause capacity changes of a concentric condenser. The current results (date, time and water level) are registered in a non-volatile store (data do not disappear after power shut-down), allowing up the registration of to 2048 measurements. The frequency of the measurements can vary between 1 and 1440 minutes. All of the limnimeters have been set to a 30-minute frequency, which allows a continuous 30-day record. A 12V accumulator supplies the device. Since spring 1999, automatic rain gauges have been installed in the Chochołowska valley (in the Polana Chochołowska, near the mountain hut) and on Hala Kondratowa (near the mountain hut).

TATRA VAUCLUSE SPRINGS

Automatic limnigraphs were installed near the main Tatra vaucluse springs: Chochołowskie, Lodowe, Bystra (Upper and Lower jointly), Goryczkowe and Olczyskie (Text-fig. 1).

Chochołowskie vaucluse spring

The vaucluse spring is situated about 30 m south of Skała Kmietowicza in the Chochołowska Valley (Niżnia Brama Chochołowska) at about 988 m. a.s.l. It flows out from beneath steep slopes built of limestones and bedded dolomites of the lower Subtatric succession (Middle Triassic). The spring has the form of a small lake with a characteristic funnel – shaped basin (about 1.6 m deep), from which water ascending two streams to the Chochołowski stream.

The main suppliers of the spring are karst systems of the Szczelina Chochołowska – Jaskinia Rybia caves (SOLICKI & KOISAR 1973, ROGALSKI 1984). Additionally, hydrogeologic data (ROGALSKI 1984, BARCZYK 1994) point to a ca. 20% supply from surface waters of the Chochołowski stream. The recharge area of the Chochołowskie vaucluse spring lies entirely within the Chochołowski stream groundwater basin and covers about 7 km^2 (BARCZYK 1994, 1998). Water capacity within the local reservoir supplying the spring is estimated at ca. 500*10^3 m^3 (ROGALSKI 1984, BARCZYK & *al.* 1999). The mean discharge in the years the 1980-2000 was ca. 400 l/s (MAŁECKA 1993, BARCZYK & *al.* 2000). Water temperature is generally constant, changing within the range 4.5-5.0 C; the chemical composition is dominated by hydrocarbonate, calcium and magnesium ions (MAŁECKA 1993, 1997). The carbonate aggressiveness (equilibrium of water with calcite) determined by the saturation index S_{ic} is –0.77, and the value of chemical denudation for karst recharge waters reaches ca. 30 m^3/km^2 per year (BARCZYK 1998a, b). The quality of water is very good, but due to easy access by tourists the springs are continuously endangered by pollution.

A water-mark and limnigraph have been installed in the exsurgent. A second water mark is present beneath the runoff of the streams towards the Chochołowski stream, at the level of the upper limit of Polana Huciska.

Lodowe vaucluse spring

The spring is situated on the eastern side of the Kościeliski stream, about 50 m from a small bridge on the track to the Mroźna Cave, beneath the contraction of a valley - Brama Kraszewskiego. It ascends from limestone debris, about 974 m a.s.l., within the contact zone of the Hightatric and Subtatric successions. The runoff takes place in an area of several tens m^2, creating a small flooding, from which water flows in three arms to the stream. The Lodowe vaucluse spring dewaters the Czerwone Wierchy Massif. Dye-tracing of karst flows carried out in the 1960s and 1970s pointed to connections of the spring with among others the Śnieżna, Czarna and Miętusia caves (DÀBROWSKI & RUDNICKI 1967). The spring recharge area reaches beyond the surface boundary of the Kościeliski stream recharge area, possibly to the south and east, covering an area of ca. 17 km^2 (BARCZYK 1994, 1998). The volume of water within the local reservoir recharging the vaucluse spring is estimated at 2000*10^3 m^3 (BARCZYK & *al.* 1999). The mean discharge in the years 1980-2000 was ca. 700 l/s. The water temperature is rather stable, within 4.0-4.5°C; the chemical composition is dominated by hydrocarbonate and calcium ions (MAŁECKA 1993, 1997). The carbonate aggressiveness (equilibrium of water with calcite) determined by the saturation index S_{ic} is –0.69, and the value of chemical denudation for karst recharge waters reaches ca. 30 m^3/km^2 per year (BARCZYK 1998a, b).

The Lodowe vaucluse spring and its direct vicinity represent a specific hydrogeological test site. Since the mid-1970s, a watermark has been present beneath the runoff of the spring waters to the Kościeliski stream as well as in the vaucluse spring itself (MAŁECKA 1996). Since 1989, a limnigraph also operates in the exsurgent.

Bystrej vaucluse springs - upper and lower

Both springs are present on the western side of the Bystra stream, about 200 m below its source. They are situated on the eastern slope of the Kalacka Turnia, 50 m below the blue tourist track to Hala Kondratowa, at about 1180 m a.s.l. and 50 m apart. Due to a slight difference in altitude, the southern runoff is referred to as the upper, and the northern one as the lower. The lower carries water continuously, while the upper spring dries up sporadically. In both cases, water descends from rock debris directly into the Bystra stream. The karst system supplying water to the springs is developed in Middle Triassic and the Upper Jurassic – Neocomian carbonate deposits of the Hightatric succession. The direct recharge area of the springs has not been determined (RUDNICKI 1967). Probably the springs dewater the Giewont Massif and the area to the south (GAŁA & GUL 1981, MAŁECKA 1993). The Bystra and Kalacka caves are situated close to both springs (the latter representing a lower, younger level of the Bystra cave), and the Bystrej vaucluse springs are considered to be a dewatering system for these caves. The capacity of water in the local reservoir recharging the spring is estimated at ca. 1200*10^3 m^3 (BARCZYK & *al.* 1999). The mean discharge for both springs in the years 1980-2000 was ca. 350 l/s. The water temperature in both springs varies within the range 4.0-4.8°C; the chemical composition is dominated by hydrocarbonate and calcium ions (MAŁECKA 1993, 1997). The carbonate aggressiveness (equilibrium of water with calcite) determined by the saturation index S_{ic} is –1.28 for the upper spring and – 0.67 for the lower spring (BARCZYK 1998b).

A water mark was installed in the Bystra stream about 150 m below the springs, allowing determination of the joint discharge for the two springs.

Goryczkowe vaucluse spring

The spring is situated on the north-western slopes of the Myślenickie Turnie in the Goryczkowy stream valley, about 1190 m a.s.l. It flows from a wide (ca. 4 m) erosional depression within the stream channel. The flow is ascending, particularly notable during lowstands. The recharge area probably covers the karstified Myślenickie Turnie Massif, the alluvial-moraine deposits filling the valley, as well as karst systems reaching the Sucha Woda stream drainage basin. The main karst system representing the external circulation (GŁAZEK 1995) is developed in Middle Triassic limestones of the Hightatric succession. Karst connections between the Goryczkowe vaucluse spring and the Sucha Woda drainage basin have been confirmed by several dye-tracing experiments the migration of water within the karst systems is dependent on the season and varies between 13 and 24 hours (DĄBROWSKI & GŁAZEK 1968, PACHLA & ZACZKIEWICZ 1981, MAŁECKA 1985, BARCZYK & HUMNICKI 1999). The volume of water in the local reservoir recharging the vaucluse spring is estimated at ca. $2700*10^3$ m^3 (BARCZYK & *al.* 1999). The mean discharge in the years 1980-2000 was ca. 800 l/s. The water temperature varies within the range 4.1-5.4°C; the chemical composition is dominated by hydrocarbonate and calcium ions (MAŁECKA 1993, 1997). The carbonate aggressiveness (equilibrium of water with calcite) determined by the saturation index S_{ic} is –0.68 (BARCZYK 1998b).

Since 1997 a watermark has been installed in the Goryczkowy stream, about 50 m below the main runoff of the spring.

Olczyskie vaucluse spring

The spring is situated on Polana Olczyska at about 1070 m a.s.l., beneath the Skupniów Upłaz, on the western side of a large pasture. Untill recently, water ascended from a depression 9 m in diameter. The depression was filled with limestone debris, sandstone and crystalline rock fragments overlying Triassic limestones and dolomites of the Subtatric succession. At present the runoff takes place from fissures in a deep (ca. 1.5m) ditch. The vaucluse spring is supplied by karst systems of external circulation from the Sucha Woda valley (Pańszczyca valley). The migration was described by WRZOSEK (1933), and confirmed by experimental dye-tracing in the 1960s and 1980s. The duration of groundwater flow through the systems of karst fissures can take over 40 hours (DÀBROWSKI & GŁAZEK 1968, PACHLA & ZACZKIEWICZ 1985, MAŁECKA & HUMNICKI 1989). Water capacity in the local reservoir recharging the spring is estimated at ca. $3400*10^3$ m^3 (BARCZYK & *al.* 1999). The mean capacity in the years 1980-2000 was ca. 780 l/s. The water temperature varies between 4.2 and 5.1°C. The chemical composition is dominated by hydrocarbonate and calcium ions (MAŁECKA, 1993, 1997). The carbonate aggressiveness (equilibrium of water with calcite) determined by the saturation index S_{ic} is –0.84 (BARCZYK 1998b).

Since summer 1997 a watermark has been installed 220 m below the runoff on the Olczyski stream.

ANNUAL CHANGES OF VAUCLUSE SPRING WATER LEVELS ON THE BASIS OF LIMNIMETRIC OBSERVATIONS

The Tatra vaucluse springs depend strongly on climatic conditions, particularly on precipitation, and on air temperature causing spring thawing of the snow cover (MAŁECKA 1993, BARCZYK 1994). Biennial observations allow comparison of the typical levels for particular springs (Text-fig.2). In all cases, the years 2000 was characterised by the higher mean annual levels than the year 1999; the annual maximum levels were also higher. This was caused by more intense snowfall in 2000 in comparison to 1999 and intense rainfall at the end of July.

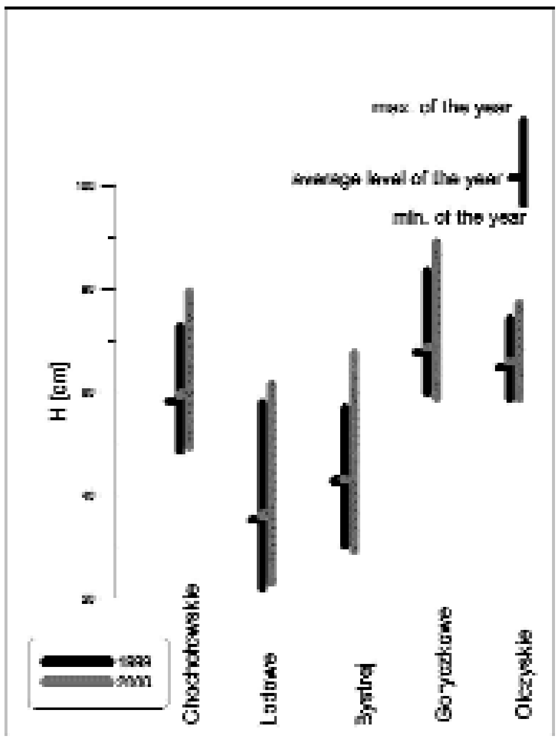


Fig. 2. Characteristic levels of the Tatra vaucluse springs in 1999 and 2000 (based on limnimetric observations)

In the case of minimal values, the situation is somewhat different. In the case of the Goryczkowe and Olczyskie vaucluse springs, the lowstands characterized by lower values were observed in winter 2000. This fact might be linked with intense snowfall, thickness of the snow cover and more complex recharge systems for both vaucluse springs e.g. in the area of the higher altitude Sucha Woda catchment area. In both years, the highest amplitudes were observed in the Lodowe vaucluse spring and the lowest in the Olczyskie vaucluse spring.

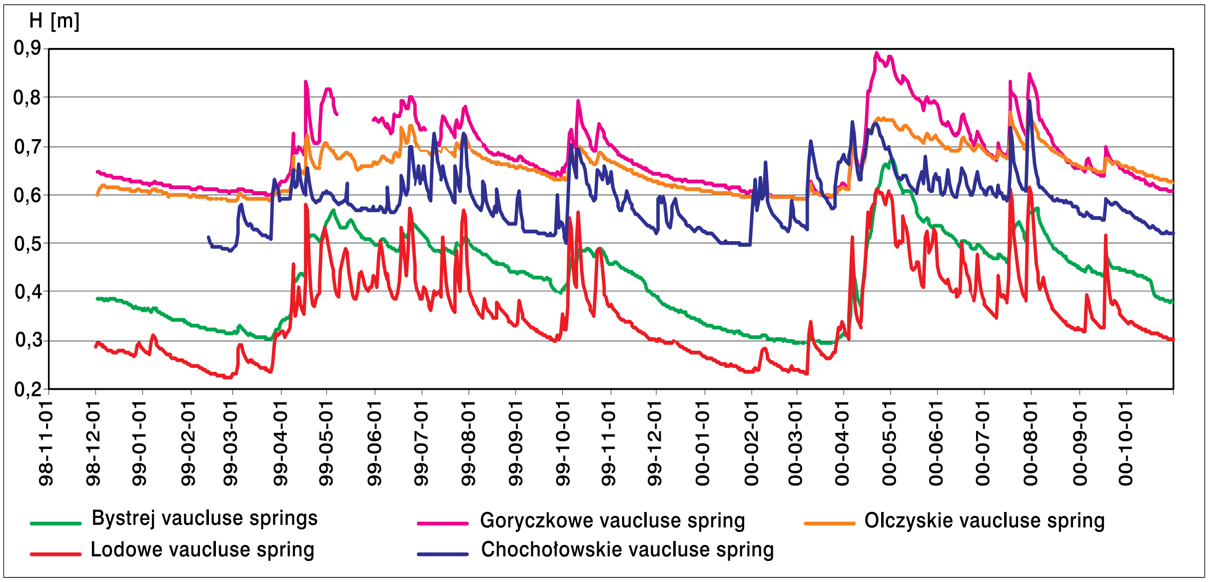


Fig. 3. Hydrograms for the Tatra vaucluse springs in the 1999 and 2000 hydrologic years

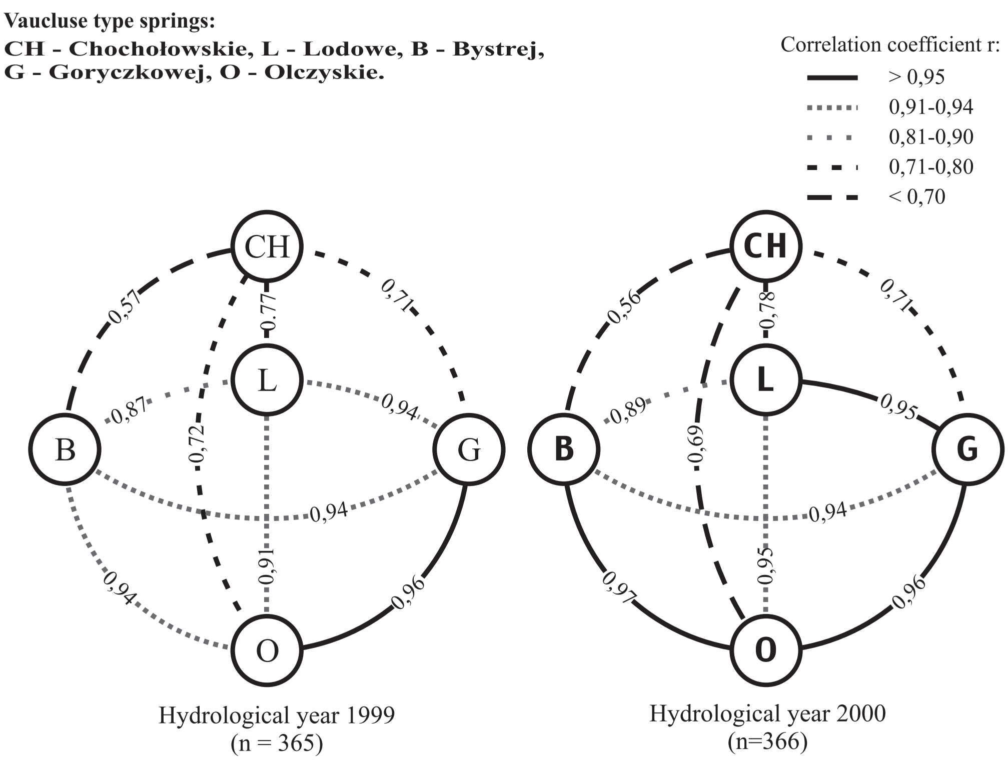


Fig. 4. Correlation graphs between mean 24-hour levels for the Tatra vaucluse springs

Many previous papers indicate the strict relationship of the reaction of the Tatra karst springs to climatic conditions, and the corresponding reaction in particular vaucluse springs. This regularity is confirmed by limnimetric observations (Text-fig. 3). According to hydrogram analysis, in all of the vaucluse springs the lowest levels were noted during the winter months: January, February and the first half of March. From the second half of March onwards, the levels increase due to melting of the snow cover. This process intensifies rapidly in April; in the following months the levels depend on precipitation, which, decreasing radically in the autumn-winter months creates a long-term regression in the vaucluse spring discharge. The lowest lowstands take place at the end of winter and are linked with the retention of precipitation in the form of snow.

Comparison of factors causing the highest levels of particular vaucluse springs, thus determining their regimes, is quite interesting. In the case of the Chochołowskie and Olczyskie springs, the highest levels result from the summer rainfall, whereas in the Lodowe, Bystra and Goryczkowy springs the highest levels occurred during thawing. This observation was particularly clear in 2000, when there was intense snowfall in the winter; however it also applied in 1999.

The Chochołowskie and Olczyskie springs are characterized by a precipitation-thawing regime, the remaining springs by a thawing-precipitation regime. The corresponding reaction of particular vaucluse springs is confirmed by analysis of the correlation coefficient r in relation to the mean 24-hours level (Text-fig. 4). The distinctly poorer correlation of the Chochołowskie spring levels with levels of the remaining springs is a characteristic feature. The latter is linked with partial recharge of the spring directly from the Chochołowski stream, determined both theoretically and experimentally (SOLICKI & KOISAR 1973, ROGALSKI 1984, BARCZYK 1994, 2000). The faster reaction of the waters of this stream to atmospheric conditions is testified by a faster increase in the spring levels and a radical decrease in the correlation coefficients with the other springs.

REACTION OF VAUCLUSE SPRINGS TO ATMOSPHERIC CONDITIONS DURING THE HYDROLOGIC YEAR

The level changes of the Tatra vaucluse springs, corresponding to changes in their discharge, depend largely on their recharge from precipitation. Even in cases of long-term water migration in the karst system, precipitation predominates in the recharge of vaucluse springs.

In the annual cycle, the first 'impulse' supplying water to karst systems is the spring thawing of the snow cover. In the Tatra Mts. the process is diverse and long-term, dependent on many factors, such as topography of the area, vegetation cover, wind and topographic level hypsometry. The main triggering factor, however, is temperature exceeding 0^{o}C (KŁAPOWA 1974). Analysis of hydrograms for vaucluse springs for the years 1999-2000 indicates that the increase in levels linked with thawing of the snow cover began at the end of March, and was caused by the prevalence of above-zero mean 24-hour temperatures (Text-fig. 5). Comparison of parameters from Table 1 and Text-fig. 4 also points to a characteristic feature of spring thawing. The hydrograms for the vaucluse springs are bi partite, with a rapid increase in the first days of March and a gentle increase between the 10^{th} March and the beginning of April. This pattern may be linked with durations of over 7 days for filling of local basins recharging the vaucluse springs (BARCZYK 1994).

During summer, the reaction of vaucluse springs to atmospheric conditions is strictly connected with the water table within the karst massif. In July and August the time of reactions, the transformation of hydrostatic pressur reaches about a dozen hours. To exemplify this relation, the reaction of the water level of the Tatra vaucluse springs to one of the larger rainfalls in July 2000 was analysed. The month in question was very rainy (Text-fig. 6), with the monthly rainfall total for Polana Chochołowska reaching 292 mm, and for Hala Kondratowa 356 mm. The most intense rainfall was observed on the 29th July (Text-fig. 6), when the daily rainfall total reached 70 and 77 mm at the respective measuring points.

The reaction of the vaucluse springs to this episode, measured to an accuracy of 0.5h, is illustrated on Text-figs 7 and 8. The rainfall began on the 26th July, reaching its culmination after 48 hours. Intense rain began at 22^{30} on the 28th July, lasting practically without breaks untill 18^{00} on the next day. The rainfall intensity was from 2 to 4 mm per 30 minutes. During a period of 19.5 hours, a total of 74 mm rainfall was recorded on Polana Chochołowska and 82 mm on Hala Kondratowa. All of the springs reacted to the rain episode by an increase in water level. The fastest reaction took place in the Lodowe vaucluse spring, where the water level increased distinctly only 6 hours after the beginning of the rainfall. In this vaucluse spring the increase in water level was fastest and began to stabilize after ca. 5 hours. A similar rapid reaction was observed in the Goryczkowe vaucluse spring; here, however, the reaction time was somewhat longer, reaching 8 hours (Text-figs 7-8). In all cases, the reaction to rainfall took from 6 to 10 hours, in the form of a more or less rapid increase in the level of the water table, followed by stabilization. A ca. 80mm rainfall lasting for almost 24 hours caused an average increase of 14 cm in the level of the water table (Chochołowskie 18 cm, Lodowe 24 cm, Bystra 5 cm, Goryczkowe 15 cm, Olczyskie 8 cm). During water level highstands in summer, such changes are linked with a considerable increase in discharges. In extreme cases, i.e. in the Olczyskie or Lodowe vaucluse springs, the discharge reached several thousand litres per second.

The analysed rainfall episode took place during the maximum filling of the massif (summer period). Because rainfalls were very frequent in summer 2000, it can be assumed that the recorded 6-8 hour reaction

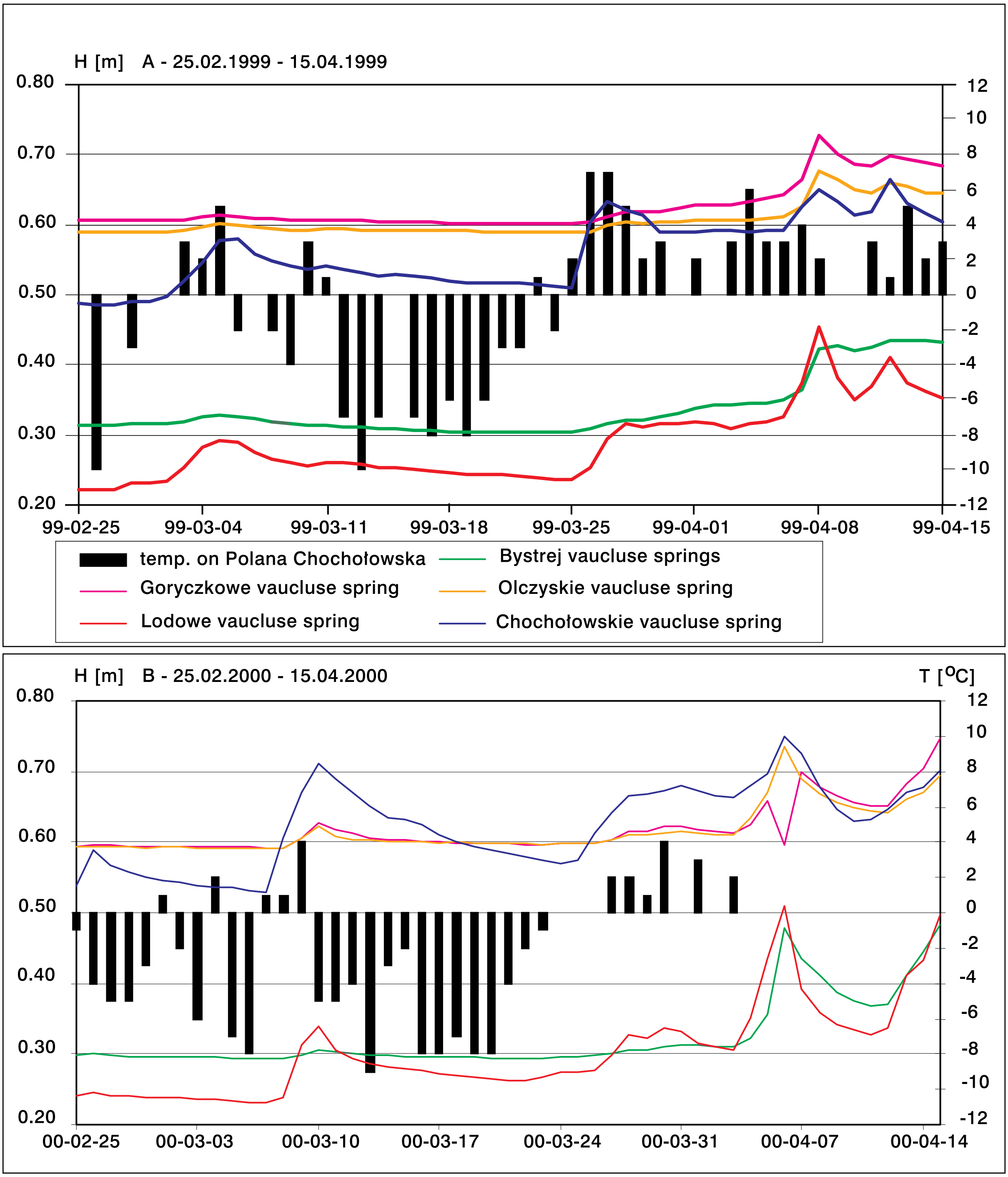


Fig. 5. Levels of the Tatra vaucluse springs in comparison to the mean 24-hour temperature on Polana Chochołowska

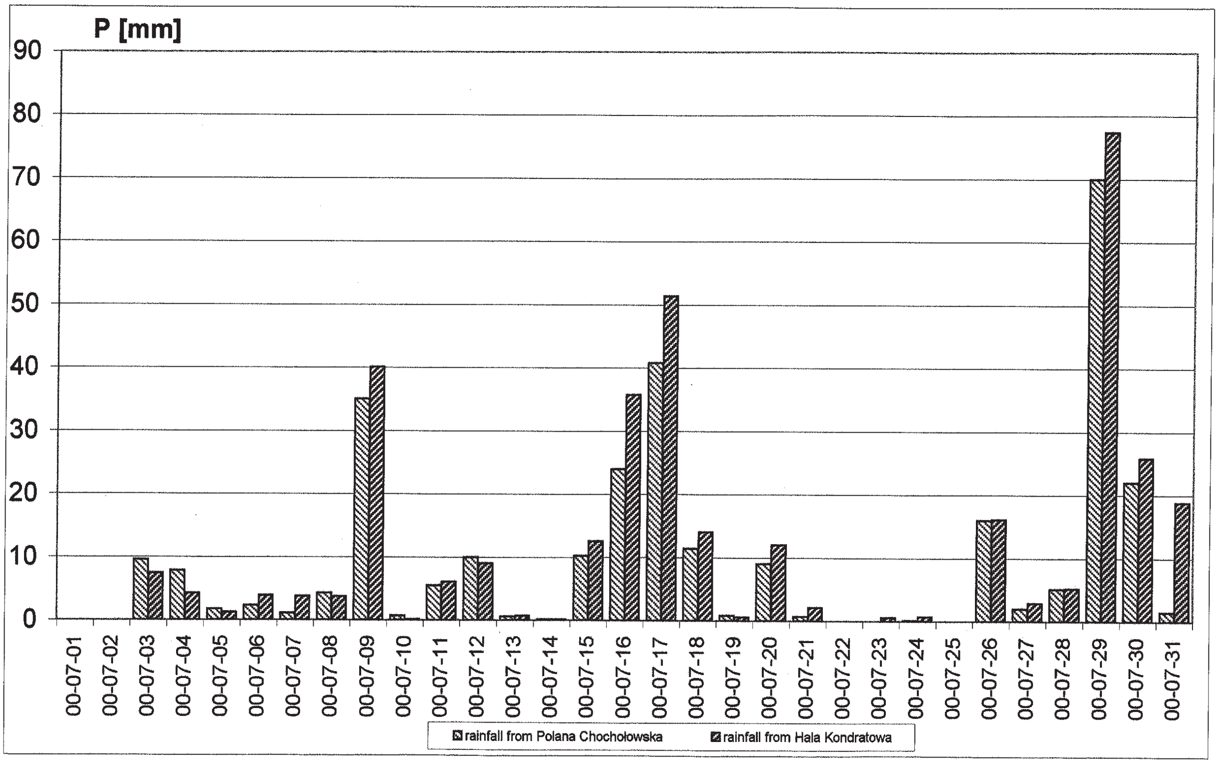


Fig. 6. Distribution of 24-hour rainfall totals for Polana Chochołowska and Hala Kondratowa in July 2000

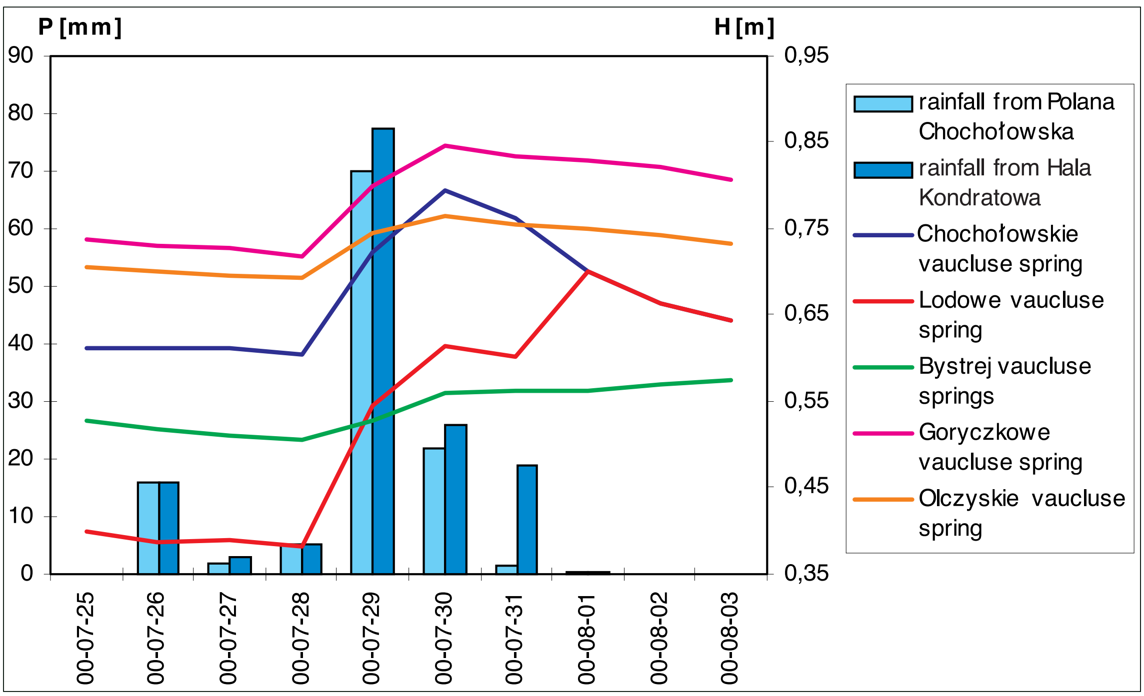
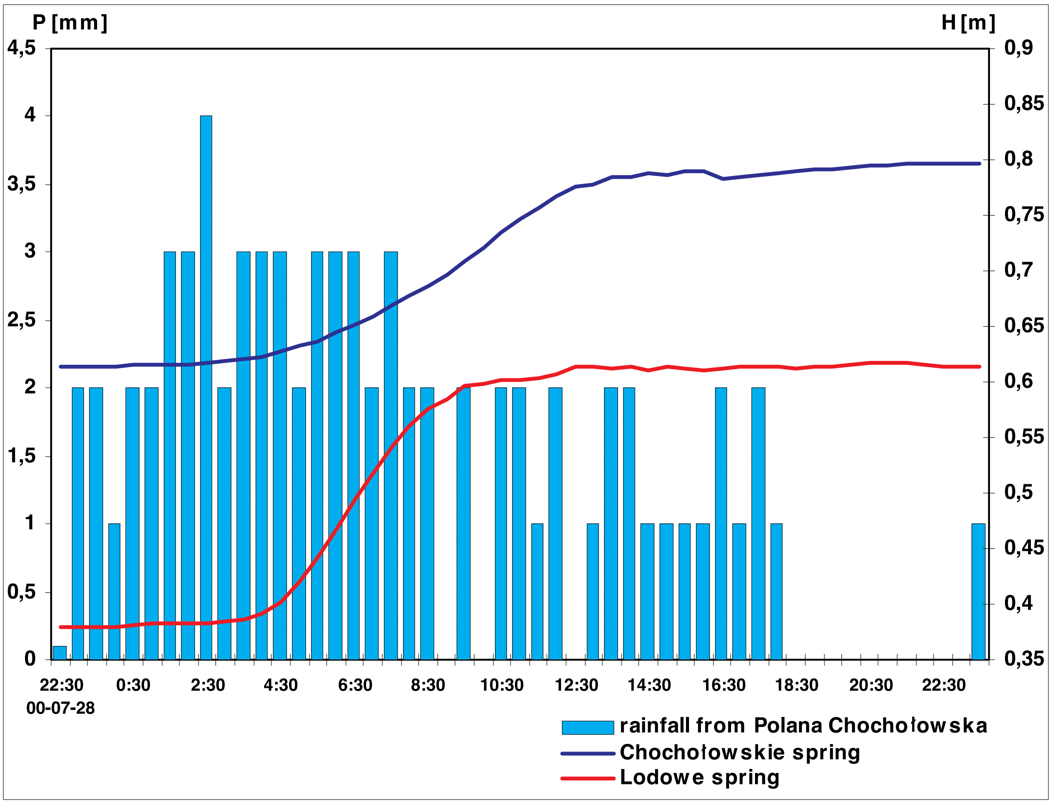


Fig. 7. 24-hour rainfall totals between 25.07 and 3.08.2000 for Polana Chochołowska and Hala Kondratowa in relation to changes in water table level of the Tatra vaucluse springs



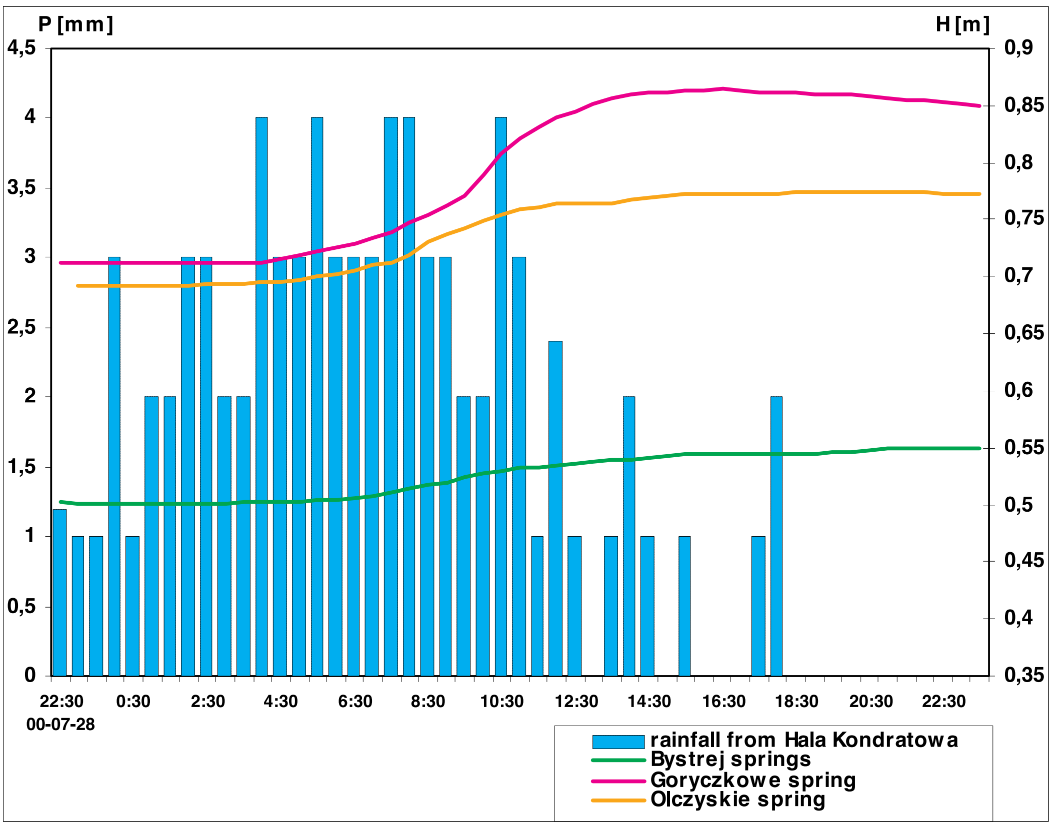


Fig. 8. Levels of the Tatra vaucluse springs in relation to rainfall

Day	water level (limnimetr) [m]	discharge [l/s]	Day	water level (limnimetr) [m]	discharge [l/s]
Chochołowskie vaucluse spring					
23.03.99	0.51	246	24.03.00	0.57	330
08.04.99	0.65	491	06.04.00	0.75	797
Δ	0.14	245	Δ	0.18	468
Lodowe vaucluse spring					
23.03.99	0.24	240	24.03.00	0.27	334
08.04.99	0.46	1706	06.04.00	0.51	2822
Δ	0.22	1466	Δ	0.24	2488
Bystrej vaucluse springs					
24.03.99	0.30	147	23.03.00	0.29	138
09.04.99	0.43	334	06.04.00	0.48	462
Δ	0.12	187	Δ	0.18	324
Goryczkowe vaucluse spring					
24.03.99	0.60	465	23.03.00	0.60	449
08.04.99	0.73	1499	07.04.00	0.70	1411
Δ	0.13	1034	Δ	0.10	692
Olczyskie vaucluse spring					
23.03.99	0.59	211	24.03.00	0.60	256
08.04.99	0.68	1683	06.04.00	0.74	6768
Δ	0.09	1472	Δ	0.14	6513

Table 1. Levels of Tatra vaucluse springs during spring thawing of the snow cover

time of the vaucluse springs to rainfall (responding to the increased hydrostatic head) represents the shortest rainfall/water level reaction time for the Tatra Mountains vaucluse springs. In any other case (other reactions to rainfall in July 2000 and earlier episodes were also analysed), the rainfall/water level reaction time were longer and, during summer, lasted for 12-24 hours.

CONCLUSIONS

To conclude, the presented detailed investigations on the reaction of the Tatra vaucluse springs to atmospheric conditions would not have been possible without limnimetric observations. The accuracy and high frequency of measurements (every 0.5h) is of great importance in scientific observations, relating to the dynamics of surface and groundwaters as well as their hydraulic links in carbonate rocks and fissure-karst massifs. They are therefore crucial in the regional analysis of hydrogeological and hydrological conditions of the entire Western Tatra Mountains.

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