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Recent Results of the Dye Tracer Tests of the Chochołowskie Vaucluse Spring karst system (Western Tatra Mts.)

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ABSTRACT:

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The region of the Bobrowiec Massif, crucial in underground flows within the Chochołowski Stream catchment area, was not studied in details until the 50ies. The Chochołowskie Vaucluse Spring is recharged mainly by karst systems, including that of the Szczelina Chochołowska - Jaskinia Rybia caves. The remaining 20% of water in the system comes from surface waters of the Chochołowski Stream. First successful dye tests were conducted on this system in 1971/1972.
The paper present's data and interpretation of the recent dye-tracer experiments for the Chochołowskie Vaucluse Spring recharge area. The results of these tests prove that the connection between the Szczelina Chochołowska – Rybia caves karst system and the Chochołowskie Vaucluse Spring is of a karst-fissure character. This hydraulic connection is a typical example of a sub-channel circulation, where flow through a karst-fissure system takes place beneath the bottom of an existing river channel. Comparing the time of dye flow through the system with water stages indicates that the system of fissures linking the sinkhole zone with the vaucluse spring is at least three fold. The inverse relation between watermark stands reflecting the degree of watering in the massif and the time, at which dye penetrates the system, is also distinctly visible.

Key words: Tatra Mountains, Chochołowskie Vaucluse spring, Karstic waters, Dye tracer experiments.

GEOLOGICAL AND HYDROGEOLOGICAL INVESTIGATIONS IN THE STUDY AREA

The Chocholowskie Vaucluse Spring (often referred to as the Chochołowskie Spring or Great Chochołowskie Spring) is located in the Tatra Mountains, Southern Poland, 30 m south from the Skala Kmietowicza in the Lower Chochołowska Gate at elevation of 988 m asl. (above sea level). It flows from beneath steep slopes built of limestones and platy dolomites of the Lower Sub-Tatric succession. Two small creeks drain the spring to the Chochołowski Stream (Text-fig. 1). The Chochołowskie Vaucluse Spring was known for its specific and exclusive for the Tatra Mts. shape and substantial depth (ELIASZ 1886), as well as for its karst nature (ELJASZ-RADZIKOWSKI 1900). Water temperature first measured in the spring was 6.4^{o} (ŚWIERZ 1897).

As the result of karst investigations in the Polish part of the Tatras in the 20-ies and 30-ies, the Chochołowskie Vaucluse Spring became known as the discharge point for the underground system dewatering the northwestern slopes of the Kominiarski Wierch and Djabliniec (WRZOSEK 1933). At that time, several caves were discovered in this area, e.g. Dziura pod Zawiesistą (Rybia Cave), Kamienne Mleko and Szczelina Chochołowska.

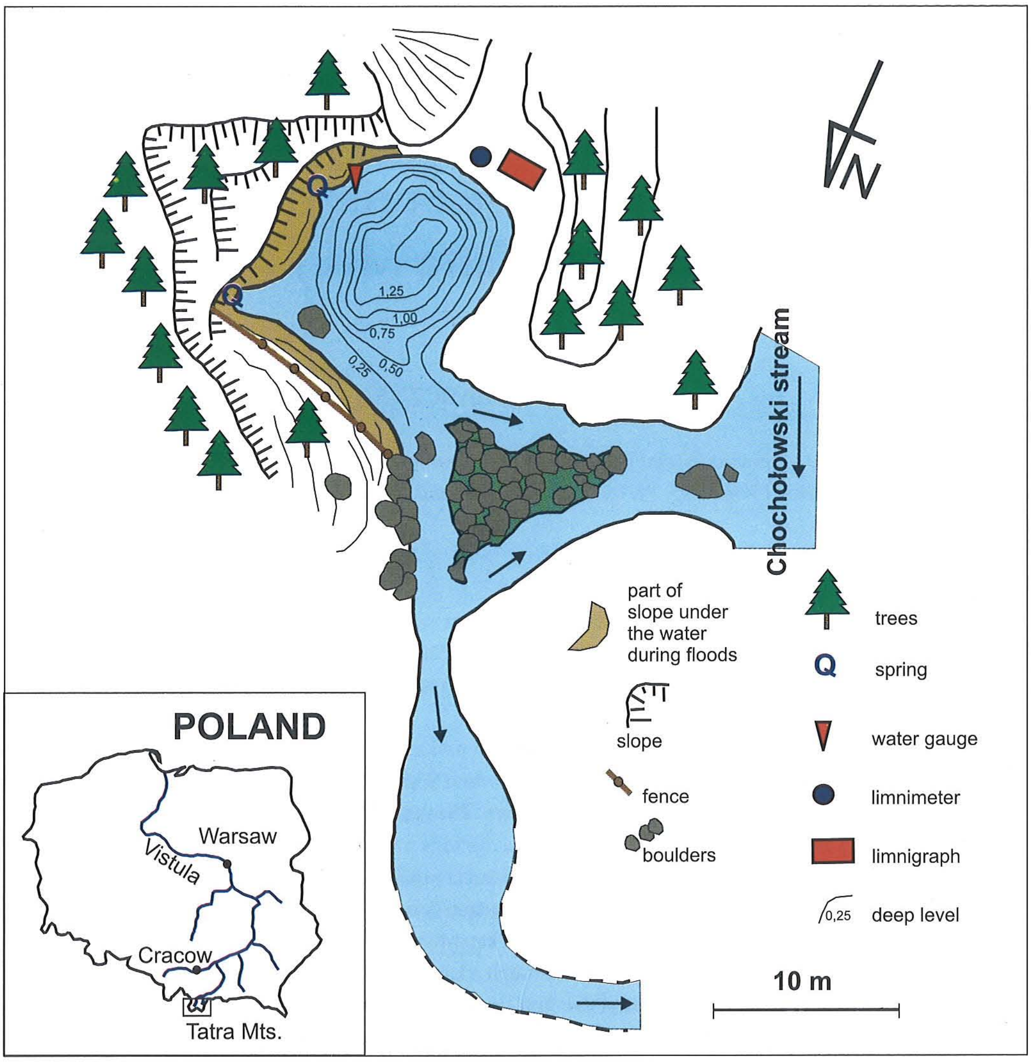


Fig. 1. Chochołowskie vaucluse spring

The region of the Bobrowiec Massif, crucial in underground flows within the Chochołowski Stream catchment area, was not a subject of detailed geological and hydrogeological investigations until the 1950-ties (Jaroszewski 1958, Wójcik 1959, 1967, Bac 1967, 1971; Rudnicki 1967).

Investigations carried out in the Szczelina Chochołowska cave clearly showed that its origin is linked with the water carried by the Chochołowski Stream and that there is no geological evidence for the existence of a system dewatering the area south of the Bobrowiecka Valley. Nowicki (1995, 2000) presented a comprehensive study of the geological setting of the Szczelina Chochołowska cave and described stages of its development.

Hydrogeological investigations carried out in the 1950-ties and later indicated the connection of the lower parts of the Szczelina Chochołowska Cave with the flow through Rybia Cave. These investigations, however, did not show any hydraulic connection with the Chochołowskie Vaucluse Spring (Kowalski 1953, Dąbrowski 1967, 1967a; Dąbrowski & Rudnicki 1964). Lack of evidence for this link induced several theories about the important role of the Chochołowskie Vaucluse Spring in the dewatering of the Kominiarski Wierch Massif (analogously to the Lodowe Vaucluse Spring in the Kościeliska Valley dewatering the Czerwone Wierchy Massif and with a recharge area outside of the surface catchment area).

At that time the only implications excluding the possible recharge beyond the surface catchment area of the Chochołowski Stream, as well as the disappearance

Fig. 2. Sketch plan of Chochołowskie vaucluse spring

waters towards the west (Bobrowiecka Valley), were catchment-area balance-calculations (MAŁECKA 1996). These calculations indicated a good balance between the recharge and runoff for this catchment area.

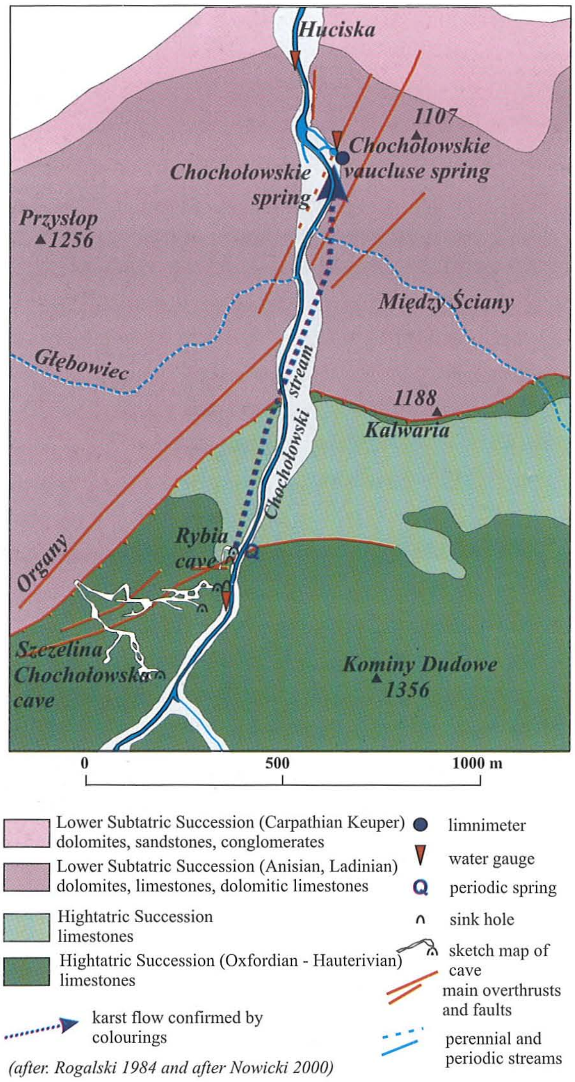
The connection determined using dye experiments between the Szczelina Chochołowska – Rybia caves karst system and the Chochołowskie Vaucluse Spring is evidently of a karst-fissure character. This connection is also a typical example of a sub-channel circulation, where flow through a karst-fissure system takes place beneath the bottom of an existing river channel.

Approximately 80% of water in the vaucluse spring comes from karst systems, including the karst system of the Szczelina Chochołowska - Jaskinia Rybia caves and the remaining 20% water in the system comes from surface waters of the Chochołowski Stream (ROGALSKI 1984; BARCZYK 1994). 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 temperature is nearly constant, changing within 4.5-5.0°C (BARCZYK 1994). The mean discharge for the 1980-1990 period was ca. 420 l/s (MAŁECKA 1997), and for the 1980-2002 period was 390 l/s (BARCZYK & *al.* 1999).

Bicarbonate, calcium and magnesium ions are dominant in the chemical composition of water (MAŁECKA 1993, 1997). The undersaturation with respect to carbonate is represented by the saturation index S_{Ic} is – 0,77 and the value of chemical denudation for karst recharge waters is ca. 30 m^3/km^2 per year (BARCZYK 1998a, b).

A water gauge, a limnigraph and an automatic limnimeter, that monitor the water level at 30-minute interval, have been installed in the vaucluse spring (Text-fig. 2). A second water gauge is present on the Chochołowski Stream near the upper limit of Polana Huciska (Text-fig. 3).

The reaction of the Chochołowskie Vaucluse Spring waters to rainwater and melt water recharge is similar to other Tatra vaucluse springs. Low stages of water during winter are not affected by short thaws. During spring thawing, the lag time, relative to atmospheric precipitation varies from several hours to 7 days. The shortest lag time observed during the summer flooding of the massif



(after: Rogalski 1984 and after Nowicki 2000)

Fig. 3. Geological sketch-map of the Szczelina Chochołowska Cave – Chochołowskie vaucluse spring karst system

PREVIOUS WORK RELATED TO DYE TRACER TESTS IN THE CHOCHOłOWSKIE VAUCLUSE SPRING SYSTEM

Solicki & Koisar (1973) reported that Zwolinski (1955) assumed an underground connection between the Szczelina Chochołowska – Rybia caves system and the Chochołowskie Vaucluse Spring. This connection, however, has never been confirmed by field investigation and, therefore, induced frequent attempts to prove this connection. Very few of these attempts were presented in literature.

Chronologically, the first information about connection was presented in the "Hydrography of the Western Tatras" (Wit & Ziemońska 1960). Regretfully, this is just a short note about the dye being introduced to the stream at Wyżnia Brama Chochołowska and occurring within the Chochołowskie Spring, but not in the Vaucluse Spring. Lack of details about this experiment makes this information not useful, and consequently it was disregarded in subsequent papers on dye tracer studies of the Chochołowskie Vaucluse Spring.

Dye tracer tests conducted in the 60ies (Tab. 1), i.e. before the connection with the Chochołowskie Vaucluse Spring was proved, focused only on the disappearance of water and its partial discharge from the system through Rybia Cave. Even though the wave flow during these experiments has been determined, comparison of the sinkhole zone storage capacity is needed to evaluate the water saturation of the massif. First documented and successful dye-tracer tests were conducted in autumn 1971 (October) and winter 1972 (February) by D. Małecka and T. Solicki (Solicki & Koisar 1973) (Table 1).

The storagae capacity of the sinkholę zone was determined (ca. 300 l/s) during the 1971 (25 October) experiment. Two an half lliters of uranine was introduced in the stream (ca. 1 km above the sinkhole zone). The dye appeared in the Szczelina Chochołowska Cave six hours later. Water colouration was observed in the vaucluse spring after 42 hours. The experiment was repeated in February 1972 during the low-water period, when there was no surface water flow in the sinkhole zone. After introducing 1l of uranine into the stream, the dye was observed in the Chochołowskie Vaucluse Spring 21 hours later (the maximal concentration was noted after 23 hours).

The next successful dye test on the Szczelina Chochołowska Cave – Rybia Cave – Chochołowskie Vaucluse Spring system was carried out between March and April 1983 (Rogalski 1984, Bobrowiec & Rogalski 1985). In this case, the dye (1020 g of uranine) was introduced directly in the Rybia Cave. Detectable concentrations of the dye were observed after more than a dozen hours (lack of precise information). The dye was noted also in the Chochołowskie Spring. The experiment concentrated on testing the method of dye detection using activated carbon for karst investigations. The absorptiveness of the sinkhole zone was determined as ca. 100 l/s, whereas the vaucluse spring discharge was estimated as 362 l/s. The capacity of water within the storage basins recharging the Chochołowskie Spring and Vaucluse Spring (ca. $580*10^{3}$ m^{3}), as well as the estimated time of water exchange (12 days) were also theoretically calculated.

In all three described experiments the mouth of the Rybia Cave remained dry.

Date	Point of dye introduction	Time elapsed for dye appearing in the vaucluse spring	Water gauge		Limnimeter data [m]	Sinkhole zone absorptiveness	Vaucluse spring capacity
			Vaucluse spring [cm]	Huciska [cm]			
24.07 1961	Sinkhole zone	Flow from Rybia Cave	Lack of data	Lack of data	Lack of data	81 l/s	Lack of data
17.09 1961	Sinkhole zone	Flow from Rybia Cave	Lack of data	Lack of data	Lack of data	92 l/s	Lack of data
14.07 1964	Sinkhole zone	Flow from Rybia Cave	Lack of data	Lack of data	Lack of data	140 l/s	Lack of data
12.08 1964	Sinkhole zone	Flow from Rybia Cave	Lack of data	Lack of data	Lack of data	110 l/s	Lack of data
25.10 1971	Stream, above the sinkhole zone	42 hours	Lack of data	Lack of data	Lack of data	300 l/s	Lack of data
Feb. 1972	Stream, above the sinkhole zone	21 hours	Lack of data	Lack of data	Lack of data	Lack of flow beneath sinkhole zone	Lack of data
19.03 1983	Rybia Cave	Several hours (15-18?)	508*	668*	0,5395*	104 l/s	362 l/s

** - values reconstructed on the basis of unpublished data of Prof. D. Małecka*

Table. 1. Results of the previous dye-test experiments in the Chochołowskie Vaucluse Spring recharge are

Date	Point of dye introduction	Time elapsed for dye appearing in the vaucluse spring	Water gauge		Limnimeter data [m]	Sinkhole zone absorptiveness	Vaucluse spring capacity
			Vaucluse spring [cm]	Huciska [cm]			
25. 09 2000	Directly to sinkhole zone	43.0 hours	509	682.5	0.5804	141 l/s	337 l/s
23. 09 2000	Directly to sinkhole zone	18.0 hours	508	685	0.5681	150 l/s	327 l/s
20. 10 2001	Directly to sinkhole zone	15.5 hours	508.5	677.5	0.6154	120 l/s	410 l/s
15. 02 2002	Directly to sinkhole zone	13.5 hours	513	678	0.6047		391 l/s
04. 04 2002	Directly to sinkhole zone	13.2 hours	511	680	0.6023		387 l/s
22. 06 2002	Directly to sinkhole zone	13.7 hours	512	685	0.6634		522 l/s
26. 06 2002	Directly to sinkhole zone	13.5 hours	511	682	0.6542		498 l/s
09. 07 2002	Directly to sinkhole zone	13.4 hours	510.5	678	0.6428	122 l/s	471 l/s
06. 08 2002	Directly to sinkhole zone	13.2 hours	511	678	0.6358	90 l/s	456 l/s
12. 08 2002	Directly to sinkhole zone	12.0 hours	509	680	0.6223		426 l/s
20. IX 2002	Directly to sinkhole zone	13.4 hours	511	684	0.6362	102 l/s	456 l/s

- colouration experiments carried out by undergraduate students of the Institute of Hydrogeology and Engineering Geology, Faculty of Geology, University of Warsaw, supervised by the author.

Table. 2. Results of the recent dye-test experiments in the Chochołowskie Vaucluse Spring recharge area

RECENT DYE TESTS FIELD EXPERIMENTS

Experiments described in this paper took place during the summer and autumn of 2000, during the implementation of the project "Determination of the retention potential and dynamics of the denudation of karst areas in the Polish Tatra Mts. based on the monitoring results for the vaucluse springs" funded by the State Committee for Scientific Research. These investigations are in progress with 11 dye-tests experiments being conducted by the end of 2002. Experiments included four types of measurements: flow time between sink hole and spring, water levels, o storage capacity of the sinkhole zone and discharge of spring during experiments (Tab. 2). In each case the dye was introduced directly into the sinkhole zone.

Results in Table 2 mostly represent intermediate water levels, which ranged from 508 cm to 513 cm in the Vaucluse Spring and from 677.5 cm to 685 cm in Huciska. Vaucluse Spring discharge ranged in these experiments from 327 l/s to 522 l/s and the dye used in experiments appeared in the vaucluse spring between 12 hours and 43 hours after the dye was injected.

In addition to the results presented in Tab. 2, the dye was observed in water flowing from the mouth of the Rybia Cave. during two measurements at very high water stages – in July 2001 and May 2002. The dye appeared ca. 15 minutes after its introduction in the sinkhole zone. At the same time, the dye was not observed in water flowing out of the vaucluse spring.

INTERPRETATION OF RESULTS

Results of the recent experiments coupled with interpretation of previous experiments indicate that the dye arrival time varied significantly despite the identical water level stages and similar storage capacity of the sinkhole zone. This data indicate that the system of fissures connecting the sinkhole zone with the vaucluse spring is complex and include three components:

■ the shortest system linking the sinkhole zone with the Rybia Cave is used at very high water stages (520 cm, 700 cm and more than 70 cm for the vaucluse spring, Huciska and limnimeter locations, respectively). The flow is extremely fast and turbulent, and the time between introducing the dye into the sinkhole and its flow out of the Rybia Cave varies between 10-15 min.

This type of flow is probably linked with a system of fissures developed in calcareous deposits of the High-Tatric series (Nowicki 2000) (Text-fig. 3), mainly Malmian-Neocomian massive limestones, Doggerian crinoid limestones and Liassic sandy limestones representing the Bobrowiecka series (Kotański 1961). The fissures are associated with the overthrust zone (Bac 1971). In this area, at very high water stages almost the entire flow utilises the contemporary developing connection between the Szczelina Chochołowska and Rybia caves (flow in a karst intermediate zone – Pulina 1999). Because the water most probably uses large fractures, and the low flow velocity does not promote water mixing, the most of the dye surficially reaches the mouth of Rybia Cave. During such high water stages the sinkhole zone absorptiveness is difficult to determine (measuring the flow absorptiveness is impossible). The vaucluse spring discharge at such high stages is 900 l/s or more, based on the limnimeter data.

■ the most frequent are dye experiments carried out during medium water-level stages (for the limnimeter 0.6-0.65m). The dye flow time through the system, is about 13-14 hours. The mean discharge of the Chochołowskie Vaucluse Spring at these water-level stages is 451 l/s, and the sinkhole zone absorptiveness is about 100 l/s.

In this case the water utilises the fault zone of the Siodło dislocation trending SW-NE from Wielkie Turnie on the slopes of Bobrowiec to the Lejowa Valley. Near this dislocation, the Middle Triassic that comprises dolosparites and platy dolomicrites, is strongly deformed with at least two parallel faults. Strong platy schistosity, parallel to axis of the dislocation, is observed within the dolomites within the dislocation zone, (Bac 1971). Fissures associated with this dislocation zone are directly linked with the sub-stream part of the karst channel as the current channel of the Chochołowski Stream lies directly above the discontinuity zone. It is likely that small fissures existing within this zone allow for some recharge of the underground flow by the surface water. The farthest portion of the karst channel is associated with NNE-SSW faults, terminating the overthrust of a block-type Głebowiec slice. The vaucluse spring outflow is located within these faults. These faults cut Triassic white dolomites building also the Niżnia Brama Chochołowska (Skała Kmietowicza). Further to the north lies the Polana Huciska eroded in clastic Keuper deposits and in Rhaetian and Liass marls and shales. The occurrence of such incompetent rocks is not favourable for the permeability of the fissures in dislocation zones and for the outflow of water on the surface. Both parts of the underground flow take place in the phreatic (active) zone (Pulina 1999, Palmer 2000).

■ the last part of this fissure system is utilised probably only during the lowermost saturation of the massif (water stages in the limnimeter below 0.60 m), when the volume of water within the massif is lowest. During such low saturation the vaucluse spring recharge rate varies between 300 and 350 l/s, at a considerable sinkhole zone storage capacity of 100 l/s and higher. It is worth noting that the vaucluse spring recharge at 300 l/s is linked with the drainage of a regional reservoir (BARCZYK et *al.* 1999). A second appearance of dye in the vaucluse spring after almost 6 days from the beginning of the dye experiments in the 1980ties (ROGALSKI 1984, BOROWIEC & ROGALSKI 1985), is probably linked with this "low-water stage" portion of the karst system.

The inverse relation was observed between the water stages reflecting the degree of the massife saturation and the time of dye arrival. The correlation and determination coefficients for points characterising the vaucluse spring recharge area are relatively high, r = - 0.72, R^2 = 0.52 for the limnimeter and r = - 0.68, R^2 = 0.47 for the water gauge. Similar inverse relationship was observed for the system recharging the Goryczkowe Vaucluse Spring (BARCZYK & HUMNICKI 1999). In both cases formulas describing the relationships of the flow time between sink hole and spring (X) on the saturation state (Y – water level measured in limnimeter) are linear correlation: Y = - 0.9843 × X + <None>926.53 for the Goryczkowe Vaucluse Spring and Y = - 0.0128 × X + 0.8012 for the Chochołowskie Vaucluse Spring. If all three components of the system are analysed, including the system linking the sinkhole zone with the Rybia Cave, this relation is even stronger (Text-fig. 4).

The presented data on the water circulation in the recharge system of the Chochołowskie Vaucluse Spring indicate the system complexity. It can be assumed that surface water comprising 25-30% of the vaucluse spring recharge utilises the entire described Szczelina Chochołowska Cave – Rybia Cave – Chochołowskie Vaucluse Spring system. Groundwater from calcareous karts regions of Wielkie Turnie and Zawiesista Turnia probably also uses this system. Determining the water contribution from the western parts of the catchment area in the recharge of the Chochołowskie Vaucluse Spring, in relation to recharge from the Kominiarski Wierch Massif, is extremely difficult if done only based on the hydrological analysis.

An additional element complicating the interpretation of results are rather rapid changes occurring within the system. The best example is the first part of the described fissure-karst system linked with Rybia Cave. Comparison of the latest data with data from the 1960ties clearly indicates that distinct changes took place within this part of the system during the last 30 years. According to archival data (DĄBROWSKI 1967, 1967a), the flow between the sinkhole zone and the Rybia Cave took place at much lower water-level stages. The measured flow upgradient from the sinkhole zone at that time were 150

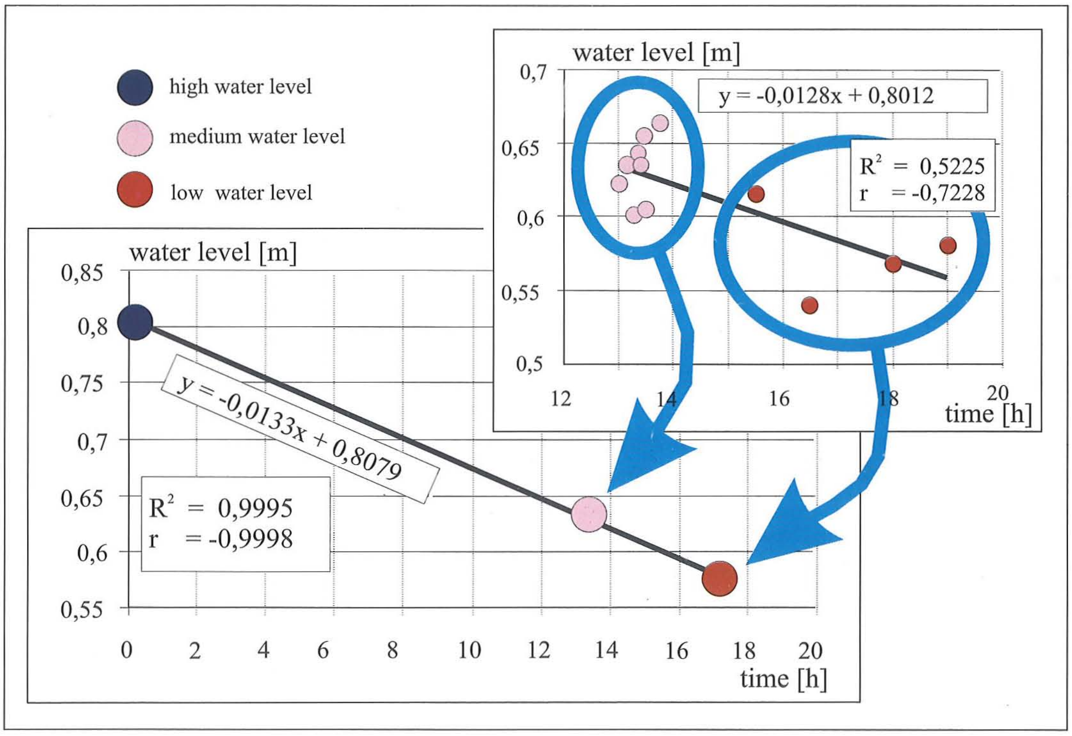


Fig. 4. Correlation between water level and time which dye appears in the vaucluse spring

to 300 l/s, whereas at present time the recharge to the Rybia Cave takes place at the flow rates exceeding 1000 l/s. The arrival time has also changed. In the 1960ties it varied between 20 and 60 minutes, and at present it does not exceed 15 minutes. Most probably the erosional activity of the Chochołowski Stream waters caused the deepening of the stream bottom, and as a result circulation within the transitional zone moved into the lower, much narrower parts of the fissures, whereas the connections that were active earlier are utilised at the flood stages. This theory might be confirmed by the fact that DÀBROWSKI (1967A) in his publications indicates two characteristic places, in which the flow vanishes (the second sinkhole was located ca. 45m below the currently existing sinkhole, halfway from the mouth of Rybia Cave). The described fissures at present occur well about 40 cm above the water table and are covered by water only sporadically.

These changes are not so distinct in the permanently saturated zone, i.e. the remaining parts of the system connecting the sinkholes of Wyżnia Brama Chochołowska with the Chochołowskie Vaucluse Spring. Nevertheless, even in this case the lowering of the groundwater table could have resulted in the slower flow.

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