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Circulation in present-day karst systems sourcing the vaucluse springs in the Polish Tatra Mts., based on tracer methods and limnimetric observations

Grzegorz BARCZYK

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The paper reviews research into karst system recharging the vaucluse springs in the Tatra Mts. Investigations of present-day karst systems are carried out directly with tracer methods, as well as based on interpretations of stationary observations in springs. Direct methods lead to the determination of groundwater migration routes and their rates, with further information from interpretations of results obtained from monitoring the vaucluse springs of the area.

Grzegorz Barczyk, Faculty of Geology, Warsaw University, Al. Żwirki i Wigury 93, PL-02-089 Warszawa, Poland; e-mail: gb59@geo.uw.edu.pl *(received: December 14, 2001; accepted: September 11, 2002).*

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INTRODUCTION

Vaucluse springs (Fig. 1) discharging water from vast karst-fissure systems represent an important source of information on the hydrography of a given karst area. In the Polish Tatra Mts., karst processes develop on relatively restricted areas within outcrops of limestones and dolomites in strongly folded sedimentary rocks. Within the overthrusted tectonic units (Sub-Tatric and High-Tatric series), non-permeable rocks separate the karstifying carbonate rocks. In the High-Tatric series the most intense development of karst takes place in Mid-Triassic limestones and dolomites, as well as in Jurassic and Cretaceous limestones. In the Sub-Tatra series the karstifying rocks are represented by Mid- and Late Triassic dolomites and limestones (Głazek, 1995). The main vaucluse springs of the Tatra Mts. occur within the contact zones between the karstifying rocks and the poorly or non-permeable rocks. The circulation of groundwater in the karst systems of the vaucluse springs represents a crucial focus for investigations into the karst of the Tatra Mts. The recognition of these karst groundwater systems can be divided into four stages:

— initial stage — theoretical determination of recharge areas and underground flows, based on knowledge of the geological setting, lithology and tectonic structure of the massif;

— practical confirmation (tracer methods) of the sink-hole — vaucluse spring and cave — vaucluse spring connections; at this stage these are individual experiments;

— permanent hydrological observations of the assumed recharge area, repeated tracer dye studies and recognition of new connections;

— precise determination of the recharge area based on tracer methods, stationary observations in connection with meteorological observations and calculation of hydrogeological parameters.

Very often, the stages follow directly each other or take place simultaneously, although occasionally there can be lengthy intervals between the particular stages.

Because of natural environmental variations, investigations of the groundwater circulation in particular systems of the Tatra Mts. vaucluse springs at present are at different stages of development.

INITIAL INVESTIGATIONS

Large vaucluse springs have been a topic of interest ever since the mid-XIX century. Between 1829 and 1860 L. Zejszner carried out systematic hydrographic observations in the Tatra Mts. (Głazek, 1995), which were published in two

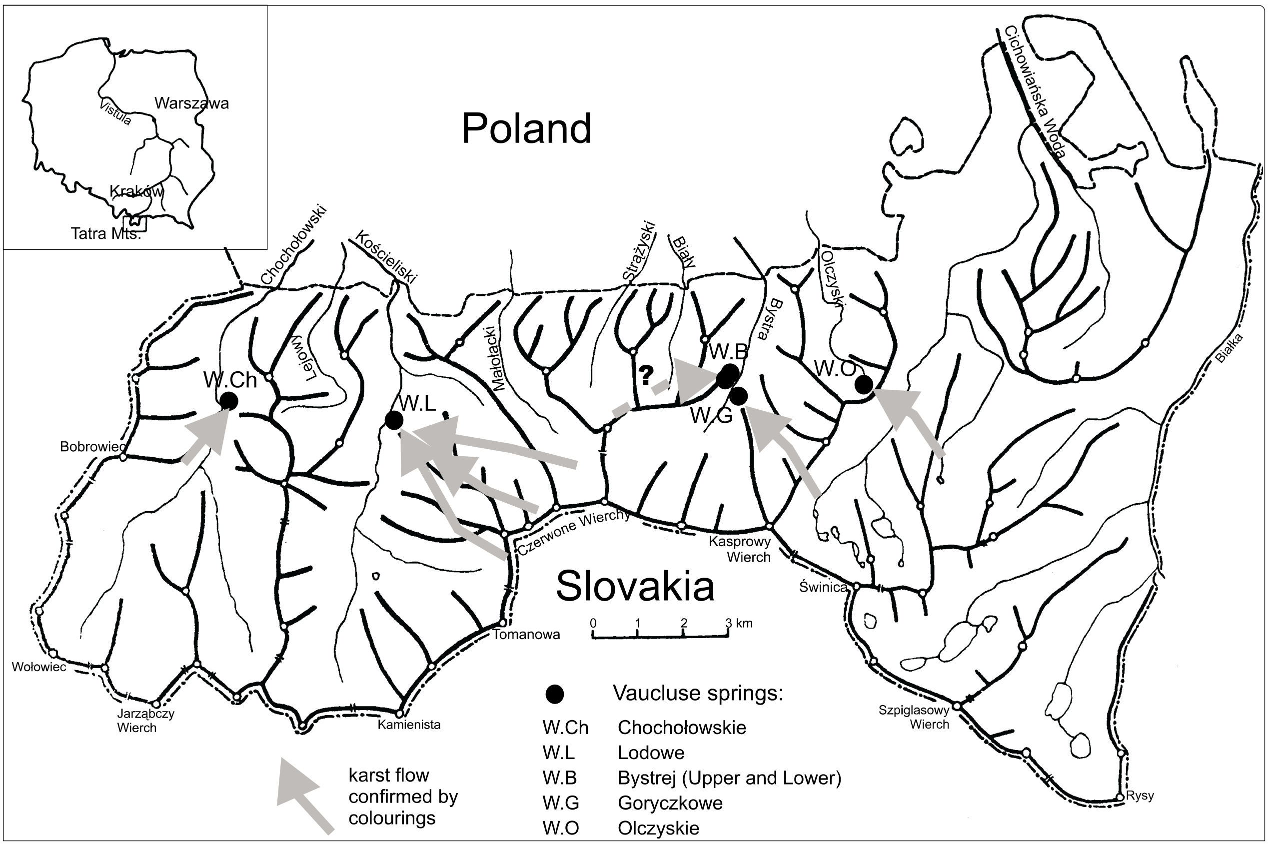

Fig. 1. Location sketch-map of the vaucluse springs in the Polish Tatra Mts.

monographs (Zejszner, 1844, 1852). Subsequently, scientific information on such vaucluse springs as the Chochołowskie, Lodowe and Bystre started to appear. Moreover, Zejszner introduced the Polish term for a vaucluse spring (Szaflarski, 1972), based on a local word for a large outflow from beneath the ground. The intense development of investigations into Polish karst took place in the 1920's and 1930's; it was focussed, however, mainly on exploitation problems. Individual hydrogeological investigations of the vaucluse springs were not carried out, although the monograph on karst phenomena in the Polish Tatra Mts. by Wrzosek (1933) is notable. The monograph presented the first theories of theoretical recharge areas for the vaucluse springs (first stage):

— the Chochołowskie vaucluse spring was considered as an outlet of an underground system dewatering the northwestern slopes of Kominiarski Wierch and Djabliniec;

— the Lodowe vaucluse spring was considered as an outlet of an underground system dewatering the area of Organy, Gładkie and Upłaz (northwestern slopes of Czerwone Wierchy);

— the Wypływ spod Pisanej outflow in the Kościeliska valley was determined as the dewatering of the Wowóz Kraków ravine, excluding its link with surface waters;

— the Bystre vaucluse springs earlier were already considered to dewater the Kondratowa valley, Giewont massif and even the eastern part of the Czerwone Wierchy massif;

— in those times, the Goryczkowe vaucluse spring was considered to be a continuation of the Goryczkowy stream disappearing above, and additionally dewatering, the Kasprowa valley;

— the periodically flooded Kasprowa Niżnia cave was linked (even in earlier times) with groundwater recharge from the Stawów Gosienicowych valley;

— the Olczyskie vaucluse spring outflow was linked with a local tectonic discontinuity; the high discharge, disproportionate to the valley size, was observed, the recharge area, however, was not specified.

The Second World War stopped the investigations on karst and its hydrogeological aspects in the Tatra Mts. for a considerable time. These resumed with a growth of interest in caves, and were carried out by the students of Professor Gołąb (Sobol, 1959; Dąbrowski, 1967; Dąbrowski and Rudnicki, 1967; Dąbrowski and Głazek, 1968; Solicki and Koisar, 1973). In the 1950's and 1960's investigations entered a second stage — the theoretically assumed circulation routes were verified practically.

At this time, the connections between the vaucluse springs and their assumed recharge areas were finally confirmed. In the case of the Olczyskie vaucluse spring, its recharge through karst systems of remote circulation from the Sucha Woda valley (Pańszczyca valley) was determined (Dąbrowski and Głazek, 1968). The time of circulation through underground systems of karst fissures was determined at over 40 hours. Tracer dye studies carried out in the area of the Gąsienicowe lakes in the Sucha Woda Gąsienicowa stream drainage basin indicated the connection of a sinkhole below the Litworowy lake with the Goryczkowe vaucluse spring. In this case the circulation of water through the karst system lasted 23 hours (Dąbrowski and Głazek, 1968).

In the Western Tatra Mts., in the Kościeliski stream drainage basin the tracer dye studies carried out in numerous caves (in new parts of earlier known caves as well as in newly discovered caves), e.g. Śnieżna, Czarna, Zimna and Miętusia caves, documented their connections with the system of the Lodowe spring (Dąbrowski and Rudnicki, 1967). At this time, short flows linked with the Wypływ Spod Pisanej outflow were documented and their connection with the surface stream were noted (Rudnicki, 1961; Dąbrowski, 1967). The connection between the Chochołowskie vaucluse spring with the Szczelina Chochołowska and Rybia caves system was confirmed basing on tracer dye studies during the early 1970's (Solicki and Koisar, 1973). Unfortunately, in most cases the experiments were not repeated, or the repetitions were not successful. In reality, besides a few tracer dye studies carried out in caves of the Czerwone Wierchy massif, linked with the Lodowe vaucluse spring outflow, during the 1970's and 1980's individual tracer dye studies only were conducted in the remaining vaucluse springs (Rogalski, 1984; Pachla and Zaczkiewicz, 1985).

STATIONARY OBSERVATIONS OF THE VAUCLUSE SPRINGS

Continuous stationary observations of ground- and surface waters in the Polish Tatra Mts. have long been carried out. In the mid 1970's, the team of Professor Małecka established an observation network, including watermarks along the main

Table 1

Correlation coefficient *r* between the mean 24-hour water levels in the vaucluse springs

Vaucluse springs	CH	L	B	G	O
	hydrological year 1999				
Chochołowskie (CH)	–	0.77	0.57	0.71	0.72
Lodowe (L)		–	0.87	0.94	0.91
Bystrej (B)			–	0.94	0.94
Goryczkowe (G)				–	0.96
Olczyskie (O)					–
	hydrological year 2000				
Chochołowskie (CH)	–	0.78	0.57	0.69	0.69
Lodowe (L)		–	0.90	0.96	0.95
Bystrej (B)			–	0.95	0.97
Goryczkowe (G)				–	0.95
Olczyskie (O)					–
	hydrological year 2001				
Chochołowskie (CH)	–	0.92	0.79	0.90	0.93
Lodowe (L)		–	0.85	0.96	0.94
Bystrej (B)			–	0.91	0.86
Goryczkowe (G)				–	0.97
Olczyskie (O)					–

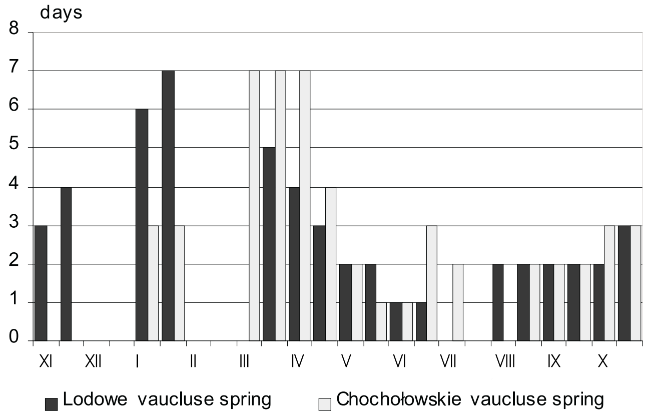

Fig. 2. Reaction time of particular vaucluse springs in the Polish Tatra Mts. to precipitation

streams in the area, right to their outlets from the massif, as well as observation sites near the largest springs and vaucluse springs. Several times a month the readings from watermarks were checked (mainly by the employees of the Tatra Mts. National Park). With few changes, the network operates till the present. The interpretation of the results obtained supplied the database for many studies on the hydrogeology of the Tatra Mts. (Małecka, 1984, 1985, 1993, 1996, 1997; Małecka and Humnicki, 1989; Humnicki, 1992). The observations included the measurements of the watermark states four times each month. These investigations, with particular attention paid to the role of vaucluse springs in the development of the hydrogeological regime of the area, were continued later by the team of Professor Małecka (Małecka, 1985*a,b*, 1993, 1997; Małecka *et al*., 1985; Pachla and Zackiewicz, 1985; Małecka and Humnicki, 1989; Barczyk, 1993, 1994, 1997, 1998).

The initiation of a network comprising limnigraphs and limnimetres continuously controlling the changes of water level in the vaucluse springs (Barczyk, 1998; Barczyk *et al*., 1999*a*, *b*, 2001) in the mid 1990's continued the investigations commenced by Małecka, as well as focused on the observations of the vaucluse springs. Therefore, by the end of the 20th century the development of investigations of the vaucluse spring systems in the Tatra Mts. area was, with some exceptions, at the beginning of the third stage of continuous observations and repeated tracer dye tests.

The largest, still unsolved problems are posed by the karst system which recharges the Bystre vaucluse springs. Despite their direct connection with the nearby Bystra cave, tracer dye tests determined no particular sinkhole responsible for the recharge. It is generally agreed that the recharge should take place from the carbonate Giewont massif, not excluding, however, recharge from surface flow from the higher, crystalline parts, which migrates through the cover of postglacial deposits towards the karstifying rocks. In the last two years, during the spring melt, I commenced several tracer dye tests of particular sinks and larger fissures on the southern slopes of Giewont; these attempts were, however, unsuccessful.

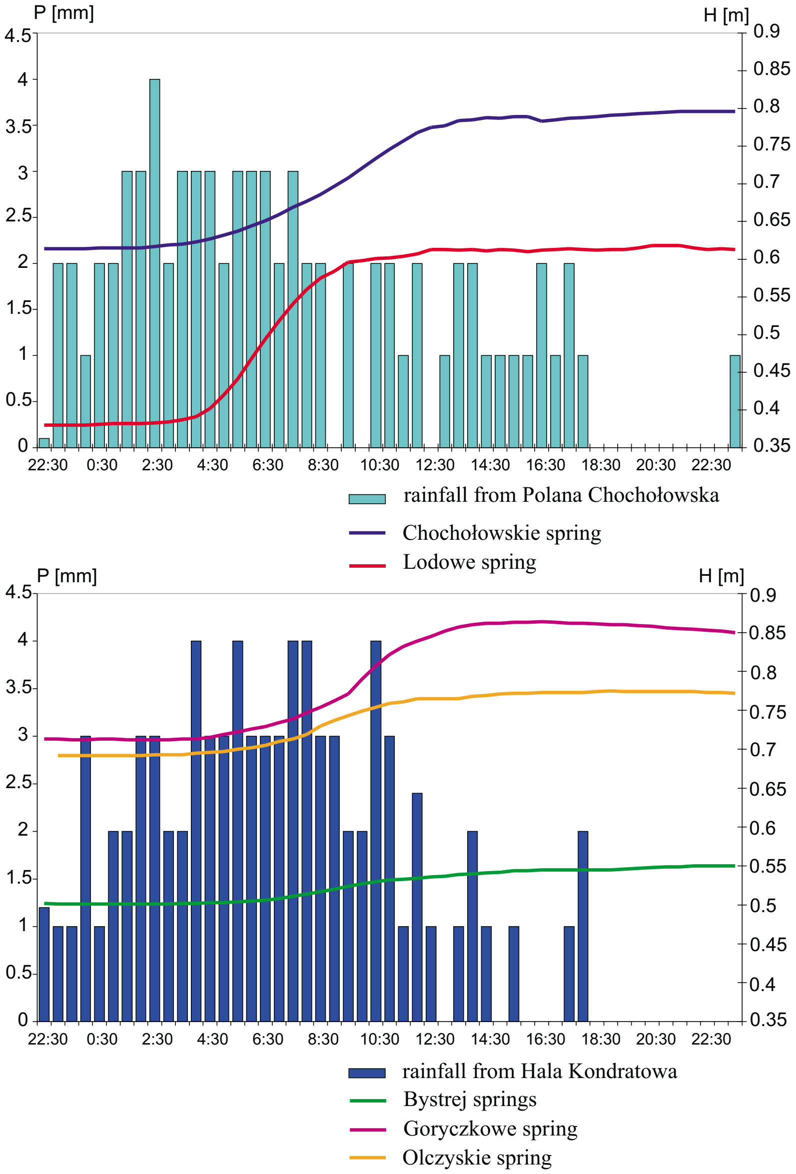

Fig. 3. Hourly reactions of the vaucluse springs in the Polish Tatra Mts. to precipitation (28–29.07.2000)

The continuous observations of water level in the vaucluse springs, carried out since 1998 (hydrogeological year), indicate a connection between the springs (Table1) (Barczyk *et al*., 2001).

The correlation between particular vaucluse springs indicates that they react in a similar way to atmospheric conditions. The weaker correlation of the water levels in the Chochołowskie vaucluse spring in comparison to other vaucluse springs is a characteristic feature. This might be linked with the theoretically and experimentally confirmed partial recharge of this vaucluse spring directly from the Chochołowski stream (Solicki and Koisar, 1973; Rogalski, 1984; Barczyk, 1994; Barczyk *et al*., 2000*a*). The more rapid reaction of waters of this stream to atmospheric conditions is reflected in the faster increase of water level in the vaucluse spring and a radical decrease of the correlation coefficient with other vaucluse springs.

Continuous observations of the watermark levels (every 30 minutes) also allow the analysis of timing and reaction to precipitation, crucial for the water circulation in karst systems. Over the annual cycle, the initial "trigger" supplying water to the karst systems is the snow cover melting. In the whole Tatra Mts. this is a variable and long-term process, depending on many factors, such as exposure, plant cover, winds and, hypsometry. The analysis of hydrograms for particular vaucluse springs for the 1999–2001 interval indicates that the increase of water levels linked with the snow cover melt begins by the end of March and is caused by the prevalence of mean 24-hour temperatures above 0°. The hydrograms are distinctly bipartite, with a rapid increase in the first days of March and a gentle increase between the second week of March and the beginning of April. This pattern can be linked with the timing of filling of the local reservoirs

Table 2

Results of tracer analyses of the Goryczkowe vaucluse spring system

No.	Date	Authors	Time [h]	Flow velocity [m/h]	Discharge [dm^3/s]	Water-level gauge [cm]					
						Z	G	K	B_K	H	L
1	summer 1964	Głazek and Dąbrowski	23	120	–	157*	–	–	220*	172*	–
2	25.06.80	Pachla and Zaczkiewicz	10	275	1597	–	602	929	222	157	78.3
3	20.09.80	Pachla and Zaczkiewicz	23	120	966	–	596	917	220	160	70.7
4	12.10.96	Barczyk, Humnicki, Parcheniak and Obuchowska	21.5	128	966	171	596	921	210	140	74.0
–	13.02.97	Barczyk, Humnicki, Parcheniak and Obuchowska	sink hole under the snow		207	168	578	909	200	130	63.9
5	30.05.97	Barczyk, Humnicki, Parcheniak and Obuchowska	15.5	177	1243	172	599	926	218	162	78.2
6	23.07.97	Barczyk, Humnicki, Parcheniak and Obuchowska	15	183	1351	173	600	926	217	184	78.2
7	1.08.97	Barczyk, Humnicki, Parcheniak and Obuchowska	13	211	2050	173	605	930	220	180	81.5
8	4.10.97	Barczyk, Humnicki, Parcheniak and Obuchowska	23.5	117	269	169	581	918	205	164	71.5
9	8.11.97	Barczyk, Humnicki, Parcheniak and Obuchowska	16	172	1143	172	598	924	212	163	76.5
10	22.07.00	Barczyk, Dalecka and Wołowiec	12.5	220	1588	–	–	929	218	–	78.3

Z — water-level gauge on Zielony Staw Gąsienicowy; G — water-level gauge on Goryczkowy stream below Goryczkowe vaucluse spring; K — water-level gauge Kalacki on Bystra stream; B_K — water-level gauge Kuźnice on Bystra stream; H — water -level gauge Harenda on Cicha Woda stream; L — limnimeter on Goryczkowe vaucluse spring (data before year 2000 reproduced after Kalacki water-level gauge); * — average level from 06–10 1964

recharging the vaucluse springs. In the autumn-winter period, the reaction time of the water levels in the vaucluse springs is from 7 to over 14 days. From the beginning of melting the reaction times shortens to one day (Fig. 2) (Barczyk, 1994).

During summer, the reaction of vaucluse springs to precipitation is closely linked with the water content of the karst massif. In June, July and August, the time of reaction, being the transfer of hydrostatic pressure, ranges from a few to about a dozen hours. The fastest reaction is observed in the Lodowe vaucluse spring, the water level of which increases distinctly after 6 hours from the beginning of rainfall. At the same time, the process of level increase is also fastest in this vaucluse spring, leading to a stabilised state after *ca*. 5 hours. A similar rapid reaction was observed in the Goryczkowe vaucluse spring, where the reaction time is slightly longer, up to 8 hours. In all vaucluse springs the reaction to rainfall lasts from 6 to 10 hours and is a lesser or greater increase of water level, followed by a smoothing of levels (Fig. 3). This regularity was determined for years with large precipitation (year 2001), as well as for "normal" years. Therefore, the 6 to 8 hour reaction of the vaucluse springs to precipitation (as the transfer of hydrostatic pressure) is the shortest rainfall-level reaction time for the vaucluse springs of the Tatra Mts. (Barczyk *et al*., 2001).

INFLUENCE OF THE WATER CONTENT OF THE MASSIF ON DISCHARGE IN VAUCLUSE SPRING KARST SYSTEMS

GORYCZKOWE VAUCLUSE SPRING

The recognition of the water circulation in karst systems recharging the vaucluse spring requires several repetitions of the analysis. The first vaucluse spring subject to such detailed analysis was the Goryczkowe vaucluse spring (Table 2, Fig. 4). In the late 1990's several tracer dye tests were conducted here, the results of which, along with earlier results, allowed determination of a correlation between the water content of the massif drained by the vaucluse spring (the water content is represented

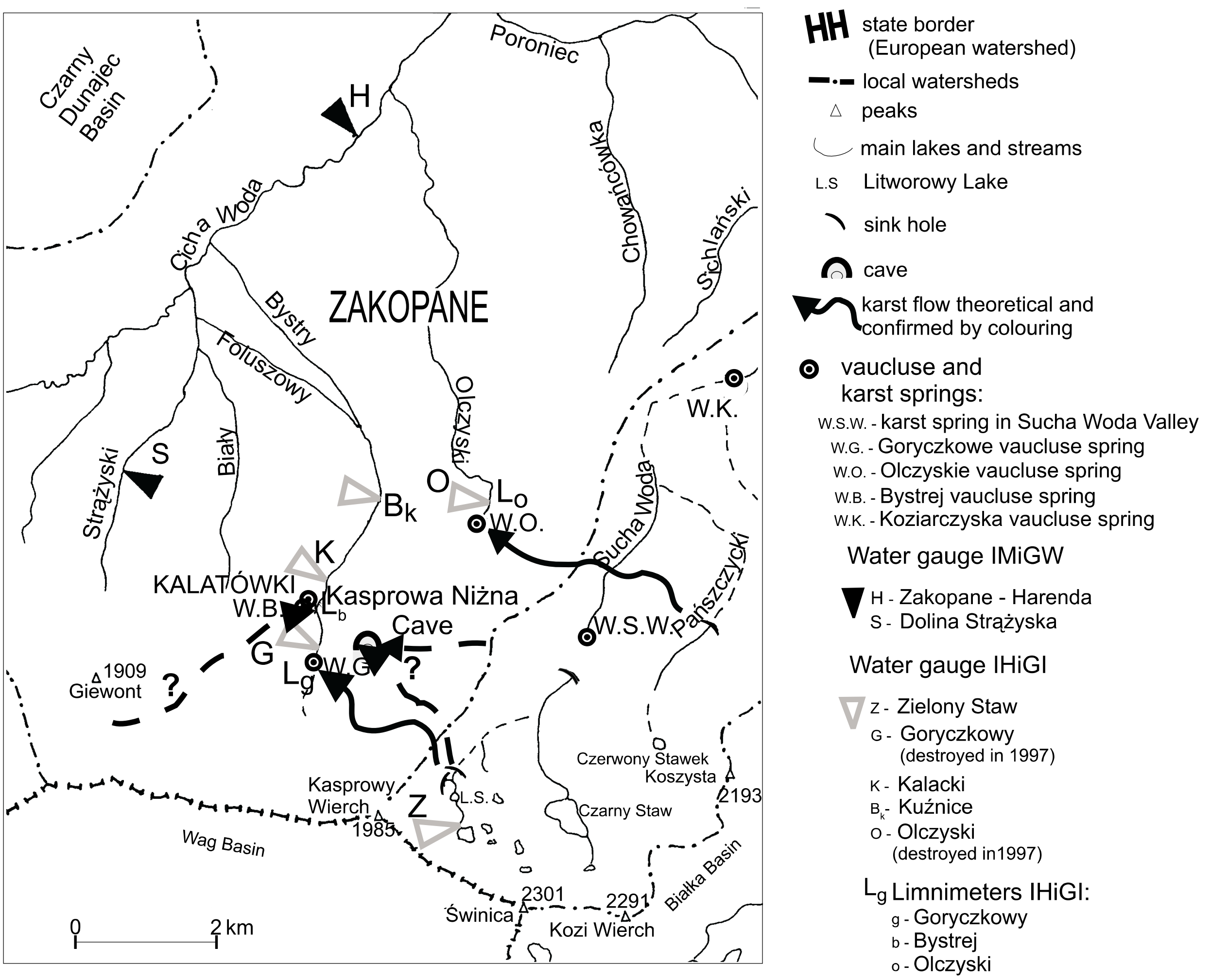

Fig. 4. Determined or presumed migration routes of karst waters in the region encompassing the Bystre, Goryczkowe and Olczyskie vaucluse springs

by surface waters flowing from the massif) and the discharge time (Obuchowska and Parcheniak, 1998). The highest correlation and determination coefficients between the water level on the water mark and the time of the tracer dye tests discharge were observed on the Kalacki watermark (K) located below the junction of the Goryczkowy and Bystry streams (correlation coefficient $r = 0.96$, determination coefficient $R^2 = 0.92$). Most probably, the fact that the watermark reflects changes in level of water not originating from a particular karst outflow, but from a larger part of the drainage basin, and therefore is linked with the entire massif (Barczyk and Humnicki, 1999), plays a crucial role in this case.

The mathematically determined relation:

$$T = -0.9843 \times H + 926.53$$

where: T — the theoretical time of wave discharge, H — the water level on the Kalacki watermark;

was confirmed during the next tracer dye test, carried out in July 2000 (Table 2).

The theoretically determined time of wave discharge from the sinkhole to the vaucluse spring, at a particular water content, was determined at 12 hours and 07 minutes; in reality the time was 12 hours and 30 minutes.

Additionally, during the analysis of discharges in the system recharging the Goryczkowe vaucluse spring, information on the periodical recharge of the outflow from the Kasprowa Niżnia cave was obtained. According to some authors, the systems recharging water to this cave are a sort of a relief channel intercepting extra water recharging the Goryczkowe vaucluse spring during melting or flooding (Wrzosek, 1933; Zwoliński, 1955). Other theories, based on the geological setting, suggest that these are independent systems separated by non-permeable Albian shales (Wójcik, 1966; Dąbrowski and Głazek, 1968). In this case the recharge of outflows of the Kasprowa Niżnia cave would take place through sinkholes in the Stare Szałasiska valley. Tracer dye tests carried out within the Goryczkowe vaucluse spring did not give unequivocal evidence of relation between the system and the cave. Continuous observations of the water level in the vaucluse springs indicate a convergence of the outflow from the Kasprowa Niżnia cave and its discharge with the respective high water levels. The outflow from fissures at the cave outlet takes place at outflows above 73.6 cm (water level on the limnimeter at the Goryczkowe vaucluse spring).

Table 3

Results of previously conducted tracer analyses in the Olczyskie vaucluse spring system.

No.	Date	Authors	Time [h]	Water-level gauge [cm]	Flow velocity [m/h]	Results
1	14.09.64	Głazek and Dąbrowski	48	–	70	+
2	25.09.78	Humnicki	–	519	–	–
3	01.09.80	Pachla and Zaczkiewicz	–	520	–	–
4	24.09.80	Pachla and Zaczkiewicz	41	522.5	85	+
5	25.10.80	Pachla and Zaczkiewicz	–	522	–	–
6	23.07.97	Barczyk and Wątkowski	–	516	–	–
7	25.10.97	Wątkowski	–	506	–	–
8	08.11.97	Wątkowski	–	509	–	–
9	28.08.98	Wątkowski	–	503	–	–

Above 77.0 cm the volume of the discharge water exceeds 50 dm^3/s, and water appears at the cave outlet.

OLCZYSKIE VAUCLUSE SPRING

In the case of the Olczyskie vaucluse spring, repeated tracer dye tests conducted in the late 1990's were unsuccessful (Table 3) (Wątkowski, 1999). Therefore information on the time of wave discharge from the recharge area in the Pańszczyca valley to the vaucluse spring are not sufficient enough to draw more general conclusions (Fig. 4). The negative results of tracer dye tests are probably a result of the wrongly selected places for the tests or by partial colmatation of the fissures.

BYSTRA VAUCLUSE SPRINGS

As mentioned above, the recharge areas for the Bystra vaucluse springs have not been determined yet by tracer methods (Fig. 4). In the near future, attempts will be undertaken to determine the sinkhole zones for the karst system recharging the vaucluse springs.

LODOWE VAUCLUSE SPRING

The karst links between caves of the Czerwone Wierchy massif and the Lodowe vaucluse (Fig. 1) spring indicated in the 1960's and 1970's were sporadically repeated in the following years. In the case of these systems, however, the repetition of tracer dye tests is complicated due to the tracer inevitable reaching the deepest parts of the caves (Table 4). Additionally, during times of increased water content in the massif, parts of the caves are inaccessible to exploration, thus hampering investigations at different intervals.

CHOCHOŁOWSKIE VAUCLUSE SPRING

The next vaucluse spring, which underwent detailed analysis of water circulation by tracer methods is the Chochołowskie vaucluse spring (Barczyk *et al*., 2000*b*). The collected data point to the complex character of the karst connections between the systems of sinkholes of the Szczelina Chochołowska and Rybia caves and the vaucluse spring (Table 5). Different migration times observed for identical water levels are particularly notable. This can be explained by the occurrence of at least two independent karst channels recharging the vaucluse spring: Rogalski (1984) has suggested this solution. The occurrence of two independent systems of channels and fissures can be confirmed by the fact that during flooding periods an outflow from the Rybia cave outlet (referred to also as the Wodna pod Zawiesistą Turnią cave) takes place and the time of tracer discharge between the sinkhole zone and the Rybia cave outlet takes less than 10 minutes. Final determination of the influence

Table 4

Caves connected with Lodowe vaucluse spring

Cave name	Hole altitude	Difference between injection point and vaucluse spring	Date of experiment
Czarna	1326 m a.s.l.	282 m	27–28.04.62 [(1)]
Miętusia	1273 m a.s.l.	86 m	1–5/6.02.86 [(2)]
Aven w Ratuszu	1867 m a.s.l.	lack of data	1986 [(2)]
Śnieżna	1703 m a.s.l.	89 m	31.08–6.09.61 [(1)]
Kozia	1850 m a.s.l.	526 m	24.05.86 [(3)]

[(1)] — after Dąbrowski and Rudnicki (1967); [(2)] — after Luty (1986); [(3)] — after Wiśniewski (1992)

Table 5

Results of previously conducted tracer analyses in the Chochołowskie vaucluse spring system

No.	Date	Authors	Time [h]	Water-level gauge [cm]			Sink hole absorptivity [dm³/s]	Discharge
				CH	L	SP		
1	25.10.71	Solicki and Koisar	42	–	–	–	300	–
2	02.72	Solicki and Koisar	21	–	–	–	flow decay below sink hole	–
3	19.03.83	Rogalski	15–18	508*	56.8	859*	104	362
4	25.09.00	Barczyk	43	509	58.0	869	140	347
5	23.11.00	Barczyk	18	508	56.8	865	150	327
6	20.10.01	Barczyk	15.5	508.5	61.5	867	120	410

* — data after prof. dr hab. D. Małecka manuscripts; CH — water-level gauge on Chochołowskie vaucluse spring; L — limnimeter on Chochołowskie vaucluse spring (data before year 2000 reproduced after Chochołowski water-level gauge); SP — water-level gauge on Chochołowski stream (Siwa Polana)

of the water content of the massif on the circulation time will be possible after the conduction of further tracer analyses.

Apart from systems recharging the vaucluse springs in the Tatra Mts. tracer analyses are applied in the present-day karst flows in the Kościeliska valley, within the Wodna pod Pisano and Wodna pod Raptawicką Turnią cave systems. In this case numerous tracer dye tests carried out during different water levels will also allow a detailed characterisation of the circulation systems.

Direct investigations of circulation in the karst systems of the vaucluse springs in the Tatra Mts., as well as application of the data from the observation network, provide further insights. Data on the discharge dynamics in the present-day karst systems, supplemented by the characteristics of physical and hydrochemical parameters of waters will enable a more complete description the hydrogeological regime of the vaucluse springs in the Tatra Mts.

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