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The thermal waters of Podhale, southern Poland: history of research, genesis and utility

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This paper outlines hypotheses relating the dip of Tatra strata beneath the Podhale Flysch to deep groundwater flow through the systems of fissures and karst caverns. Attempts by J. Gołąb and S. Sokołowski to constrain hypotheses through a series of exploratory-exploitational drillings led to the discovery in 1963 of thermal artesian waters in the Tatra foreland. These are of meteoric origin with total dissolved solids from 0.2 g/dm^3 in the Tatra area to 3.0 g/dm^3 in the central and near-Pieniny parts of the basin. Palaeogene strata are important in controlling the hydrogeology of the Podhale artesian basin. The Tatra Mountains are a recharge area for the Podhale basin whereas the Pieniny Klippen Belt seems to be an impermeable shield preventing further groundwater flow to the north. Within the southern flank of the basin the groundwaters are used as a local source of drinking water as well as to supply thermal baths in Zakopane. Furthermore, the geothermal energy from the Podhale basin provides a supply of clean, environment-friendly domestic heating.

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INTRODUCTION

The Tatra Mountains and Podhale region have long been studied scientifically, resulting with papers and maps.

The first of the groundwaters concerned mainly the Tatra massif and its foreland, as regards thermal waters and their relation to chemistry and karst development, the discovery of Jaszczurówka Therma by Zejszner (1844) is noteworthy. The seepage of rainwater through a system of fissures and karst caverns to significant depths was mentioned by Szajnocha (1891). He suggested that the origin of these waters related to the dislocation which separates the Tatra massif from the Podhale region, later termed by Gołąb (1959) the "sub-Tatric dislocation".

Evidence indicating the occurrence of tectonic breaks, principally discontinuous ones, assisting the circulation and ascent of these waters, includes:

— discernible differences in dip between Eocene carbonates and the Podhale Flysch (Mastella *et al*., 1979);

— transverse dislocations (Makowska and Jaroszewski, 1987; Ozimkowski, 1992; Bac-Moszaszwili, 1998*a*);

— recent tectonic movements (Bac-Moszaszwili 1995, 1996, 1997);

— occurrence of productive fault springs among which the best known are the Barany and Baptyści Springs (Małecka, 1993; Małecka and Roniewicz, 1997).

A detailed circulation scheme for waters supplying the only therma within the Polish Tatra Mountains was given by Gołąb (Sobol, 1959) (Fig. 1). This author suggested that the interbedded limestones and dolomites of Suchy Wierch and the limestones and conglomerates of Krokwie (according to Guzik and Kotański, 1963 — Suchy Wierch and Mała Świnica nappes) were the main recharge area. Due to their deep circulation within the strata of Suchy Wierch, the waters warm up to a temperature of about 36°C, and migrate upwards through the sub-Tatric dislocation. Here, due to mixing with shallowly circulating waters of the Krokwie succession, they cool down to about 20°C.

In spite of wide-ranging research into the geology of the Tatra Mts. and Podhale (Guzik and Kotański, 1963; Bac-Moszaszwili *et al.*, 1979; Bac-Moszaszwili, 1998*b*, 1999) Gołąb's scheme did not lose its hydrogeological significance. According to this scheme, some meteoric waters within the zone of the sub-Tatric dislocation rise, whereas others move

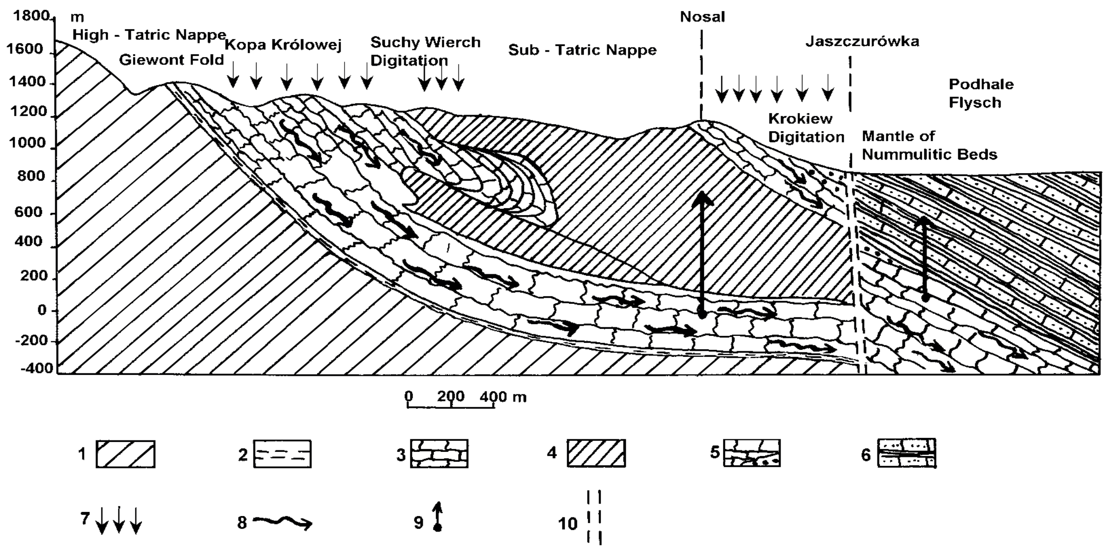


Fig. 1. Model of the origin of the Jaszczurówka Therma according to Gołąb

1 — limestones, shales and sandstones: Triassic, Jurassic, Cretaceous; 2 — shales: lower Triassic; 3 — limestones and dolomites: Middle Triassic; 4 — shales and sandstones: lower Lias–Keuper; 5 — limestones and conglomerates: Triassic and Eocene; 6 — shales interbedded by sandstones and dolomites — Podhale Flysch; 7 — infiltration; 8 — direction of flow; 9 — artesian water pressure; 10 — faults

northward, beyond the orographic boundary of the Tatra, through a system of fissures and karst caverns (Małecka, 1980), which play a fundamental role in the circulation and drainage of these waters. Research directed by Professor Gołąb and later by me has involved monitoring the springs discharging from the zone of tectonic disturbance between the Tatra Eocene carbonates and the flysch shales of the Zakopane Beds. Some 250 m east of the therma lie the system of karst caverns of the Jaszczurówka Cave. These are accompanied by two springs known as the Baptyści and Barany. During periods of low groundwater flow the total discharge of both springs fluctuate within 20 l/s. Nowadays the springs are cased and exploited to offset water shortages within Zakopane.

Thus, data gathered at the Institute of Hydrogeology and Engineering Geology of the Warsaw University, was already of a historical character as, the Jaszczurówka Therma which in the 1960's had been recharging thermal baths, now is nonexistent.

Among three sets of fissures found here, perpendicular to the Olczyski Stream, only one carried thermal waters (Fig. 2). This is evidence of the complex circulation pathways of the fissure-karst groundwater within the zone of the sub-Tatric dislocation. In the 1950's, a gradual decrease of temperature from 20.4 to 19.8°C was observed. Later, due to an influx of cool water from a set I fissure, the outflow temperature oscillated around 14–18°C. In order to reach waters of higher temperature, in 1957 Gołąb's proposed a borehole 3 m away from the fissures carrying thermal waters. During boring, the water temperature rose up to 21°C. At a depth of about 50 m, in the basal Eocene carbonates, karst caverns were found. A cave-in of boring equipment then occurred and inflow of cold water was observed, connected with middle Triassic dolomites drilled to a depth of 57–151 m below ground level (Sobol, 1959). Efforts at stopping the cold water inflow into the well failed. Nevertheless, the drilling showed that the system of karst fissures within the Eocene nummulitic limestones and middle Triassic dolomites is connected with surface drainage. This was corroborated by colorant tests as well as by measurement of flow rate in the longitudinal profile of the Olczyski Stream (Małecka and Humnicki, 1989) where, within the third (III) set of fissures (Fig. 2), recharge from surface water to the groundwater was observed.

ROLE OF PALAEOGENE FORMATIONS IN REGIONAL HYDROGEOLOGIC SETTINGS

Eocene carbonates exposed along the northern edge of Tatra Mountains have been, since Uhlig (1897), much studied, as discussed by Roniewicz (1969, 1997). In terms of hydrogeology the Palaeogene strata of Podhale constitute two different units in terms of lithology and facies. A lower unit comprises organodetrital limestones, dolomites and conglomerates, together termed the nummulitic Eocene or carbonate Eocene; the upper unit is of flysch sandstones interbedded with shales. Nevertheless, they constitute a single, jointed hydraulic system recharged by meteoric water.

Hence, outcrops of carbonate Eocene are included within the Tatra facies (Małecka, 1982). The validity of this approach is supported by the hydrochemistry of the Polish Tatra Mountains, where fissure waters of the sub-Tatric sedimentary succession and the carbonate Eocene show broad similarity (Małecka, 1989; Małecka and Małecki, 2000). Shales and sandstones of the upper unit form an isolating cover for the sub-flysch aquifers (Małecka, 1984; Małecka and Małecki, 1996).

Research studies into the natural environment and its protection over the last fifty years have contributed greatly to understanding the natural conditions of this region.

A number of statements, obvious today, years ago constituted only plausible hypotheses. The best example is the discovery of the artesian waters at temperatures qualifying them as thermal in the foreland of the Tatra Mountains.

ARTESIAN WATERS OF SUB-FLYSCH WATER-BEARING STRATA

Suggestions of Tatra strata dipping below flysch, and of water migrating through systems of fissures and karst caverns down to significant depths, prompted testing of these models by exploratory drilling. This was advocated mainly by J. Gołąb and S. Sokołowski, who submitted a wide program of geophysical and geological explorations in Podhale, aimed also at economic deposits (Sławiński, unpubl.). Their intuition led to the discovery of the geothermal nature of the Podhale basin. The first of a series of deep exploratory boreholes was the Zakopane IG 1 borehole located along the extension of the Bystra valley dislocation, on the western slope of Antałówka hill in Zakopane (Fig. 3). Due to its depth (3073 m), the variety of research carried therein (results published by Sokołowski, 1973; Dowgiałło *et al*., 1974); and long term field monitoring of the dynamics and chemical composition of the water (Małecka, 1995; Małecki, 1995), this borehole represents a benchmark, providing a background for analyses of the results of subsequent boreholes. The profile of rocks penetrated and the results of hydrogeological research revealed two water-bearing formations separated at a depth of 2000 m by a unit of mudstones and marly shales about 100 m thick. The lower formation is characterised by insignificant discharge of waters of SO_4-Ca-Mg hydrogeochemistry with total dissolved solids within 2–3 g/dm^3. The upper formation is exploited at a depth of 1540–1620 m with discharge of about 109.8 m^3/h, and temperature of 35.5°C. The characteristic feature of these waters is significant thermal and chemical stability, as indicated also by monitoring studies. They are consistently of HCO_3-SO_4-Ca-Mg hydrogeochemical composition (Małecka and Małecki, 1998). The results of the Zakopane IG 1 exploratory borehole, both scientific and economic, were undoubtedly a turning point in the recognition of the regional hydrogeologic settings of Podhale and the Tatra Mountains. However, the relationship between the shallow and deep circulating waters of the Podhale basin has not yet been determined.

Within the orographic part of the Tatra Mountains groundwaters are separated from the surface by an aeration zone. This determines their unrestrained, unconfined character and active reaction to atmospheric precipitation. The results of stationary monitoring of vaucluse springs and streams draining the northern slopes of the Tatra Mountains as well as local ascent of groundwater, or its deep penetration into the massif show that the waters of Tatra massif remain in regional hydraulic connection despite complex circulation pathways. This contradicts an earlier hypothesis suggesting the existence of many independent groundwater levels isolated from each other (Rudnicki, 1967; Różański and Duliński, 1988). Within the Tatra Mountains it is not possible to determine a unique boundary between groundwater of the unconfined water table and the confined one, which would comprise evidence of isolation of the aquifer from the aeration zone. This type of partition is possible only within the foreland of the Tatra Mountains where the Tatra facies and carbonate Eocene are covered with a compacted layer of Podhale Flysch deposits.

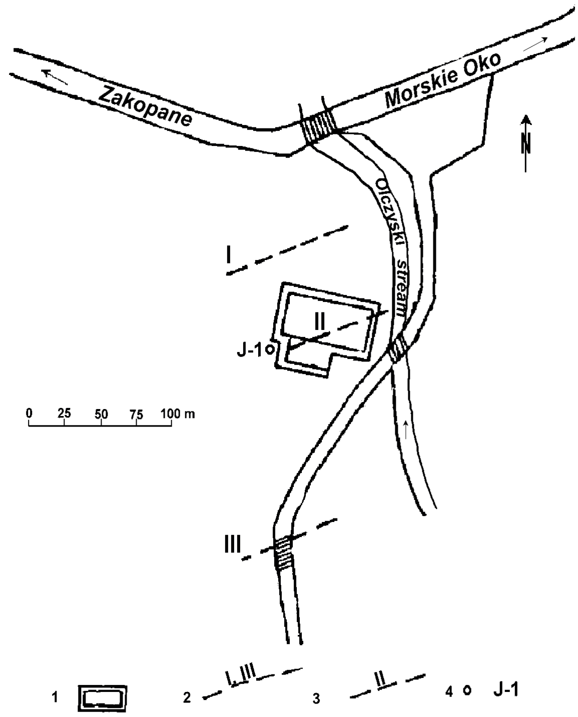


Fig. 2. Sketch of patterns of fault fissures and borehole location around the Jaszczurówka baths (after Tomczyński, 1958)

1 — bath, 2 — fissures with fresh water, 3 — fissures with thermal water, 4 — inoperative borehole

The results of boreholes and studies of water storage capacity showed that, within the flysch, the zone of active exchange of water is from a few dozen to 100 m thick (Jawański, 1973; Niedzielski, 1974; Małecka and Murzynowski, 1978; Małecka, 1981). Below this depth, the flysch sediments seem to provide an isolation cover for thermal waters of the Podhale artesian basin (Chowaniec *et al*., 1997). Systematic information regarding exploitation capabilities, thermal properties and chemical composition of waters of the southern flank of the Podhale artesian basin were provided by subsequent exploratory boreholes (Table 1, Fig. 4). The significant Zakopane 2 borehole was drilled in 1975, 12 years after discovery of thermal waters in Antałówka hill. The decision to drill that borehole was prompted by the development of the existing Antałówka baths. The well was supposed to play the role of damage or supple-

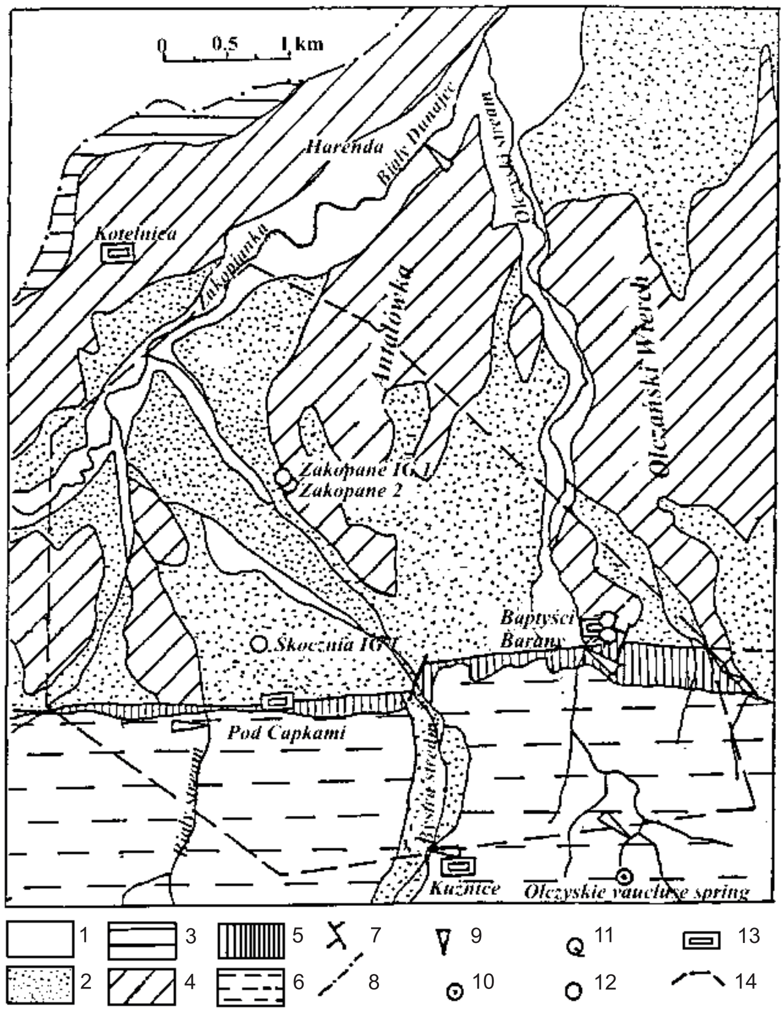


Fig. 3. Borders of the mining area of the Antałówka thermal waters

1 — alluvium, 2 — glaciofluvial sediments, Podhale Flysch; 3 — Chochołów Beds, 4 — Zakopane Beds, 5 — carbonate Eocene, 6 — Tatra Mountains — alp facies, 7 — geological division between Tatra facies and Zakopane Beds, 8 — surface divide zone of the Biały Dunajec catchment, 9 — water gauge, 10 — vaucluse spring, 11 — spring, 12 — well/borehole, 13 — municipal water intake, 14 — border of mining area

mentary for the Zakopane IG 1 thermal well and to take thermal waters from Liassic strata of the sub-Tatric unit at a depth of about 1650 m. During the drilling, after flysch sediments had been penetrated, artesian flow of water appeared from organodetrital limestones, conglomerates and dolomites of the carbonate Eocene. The temperature of water was 26.4°C, with surprisingly high yields reaching 273 m^3/h. The 24-day tests guaranteed the use of this level as an additional source of thermal water for the planned complex of swimming pools. Despite that, the depth of the well (1113 m) was about 500 m shorter than planned, the discovery of a new, thermal water-rich aquifer in carbonate Eocene strata prompting a decision to stop further deepening, after consultations with Professors Z. Pazdro and S. Sokołowski.

Information gained during drilling, as well as hydrogeological examinations of both wells, located only 80 m apart, gave very different results in case of carbonate Eocene. The fact that the carbonate Eocene in the Zakopane IG 1 well was practically water-free can be explained by the character of block tectonics in the southern flank of the Podhale basin. The first borehole encountered a monolithic block of carbonate Eocene rocks, while the other is located where sub-Tatric faults cross the Bystra valley.

When the Zakopane IG 1 well was drilled, it was believed that the recharge area of the Antałówka thermal waters was located south-east from Zakopane and comprised the Sucha Woda valley and the slopes of Goły Wierch and Kopy Sołtysie closing it from the eastern side (Sławinski, 1976). However, the results of stationary monitoring of Tatra vaucluse springs and other springs draining the outcrops of carbonate Eocene within the contact zone with Zakopane Flysch strata did not confirm this. Thus, it indicated that the whole Tatra massif participates

Table 1

Exploration/exploitation boreholes in the Podhale Artesian Basin

Borehole name and designation (no. according to Fig. 4)	Year of accomplishment	Morphological situation	Distance from Tatra [m]	Altitude [m a.s.l]	Hole depth [m]	Thickness of pierced series [m]				Aquifer	
						Quaternary	Palaeogene: Eocene - Oligocene Flysch	Palaeogene: Carbonate Eocene	Tatra series	Lithology and age of aquifer	Screen depth [m]
South flank of Podhale artesian basin											
Siwa Woda IG-1 (1)	1973	Chochołowski stream	925.0	896.5	856.0	15.5	601.7	135.4	103.4	carbonate Eocene + Tatra series — detrital dolomites, conglomerates with clayey-silica binder, floor, pelitic dolomites	617–800
Kościelisko Kiry P-1 (2)	1982	sub-Tatra rift, Kirowa Woda cone	25.0	920.0	200.0	0.8	—	199.2	—	carbonate Eocene	hole cancelled
Staników Żleb S-1, S-2 (3)	1982	divide zone between Biały and Czarny Dunajec catchment	125.0	967.0	110.1	1.4	19.6	98.1	—	carbonate Eocene — limestones, dolomitic limestones and dolomites (not pierced)	95–110.1
Hruby Regiel IG-1 (4)	1973	divide zone between Biały and Czarny Dunajec catchment	525.0	935.0	707.1	1.0	294.0	362.2	49.9	carbonate Eocene — nummulitic limestones, and dolomites	400–630
Skocznia IG-1 (6)	1986	sub-Tatra rift, Zakopane cone	720.0	883.2	700.0	12.5	482.5	61.0	144.0	Tatra series — Triasic, dolomites and dolomitic limestones, brecciated (in 2 m carbonate Eocene roof)	554.2–566.7; 598.7–642.7
Zakopane IG-1 (7)	1963	fdoot of Antałówka western slope	1680.0	864.9	3073.2	—	1000.5	118.5	1954.2	Tatra series — Lower Jurassic, marls and marly limestones with hornstones	1540.0–1620.0
Zakopane 2 (8)	1975	foot of Antałówka western slope	1600.0	868.2	1113.0	—	985.0	112.0	16.0	carbonate Eocene — organodetrital limestones, conglomerates and dolomites	1064.5–1111.0
Jaszczurówka (11)	1959	Olczyski brook valley at Tatra outlet	0.0	903.0	151.0	16.2	—	57.0	77.8	carbonate Eocene + Tatra series	not exploited
Zazadnia IG-1 (16)	1986	Filipka rivulet valley at Tatra foot	1550.0	855.2	680.0	1.0	649.0	30.0	—	carbonate Eocene — limestones in the roof part with fauna, detrital in floor (not pierced)	653.5–674.5
Basin central and northern part											
Furmanowa PIG-1 (17)	1990	watershed zone between Biały and Czarny Dunajec drainage area	4700.0	1010.0	2324.0	2.0	1985.0	53.0	284.0	carbonate Eocene — conglomerates, limestones and marly limestones; Tatra series — Jurassic, Cretaceous, silica limestones and quartzite sandstones	2003–2324
Poronin PAN-1 (18)	1989	Poroniec rivulet route	5400	741.0	3003.0	5.0	1768.0	—	1235.0	Tatra series — Middle Triasic, brecciated dolomites and limestones	1768–1855
Bukowina Tatrzańska PIG-1 (19)	1991	watershed zone between Biały and Czarny Dunajec drainage area	6500.0	957.0	3780.0	4.0	2211.0	10.0	1555.0	Tatra series — Jurassic — Cretaceous — marly limestones with tectonic mirror in floor	3045.0–3250.0
Chochołów PIG-1 (20)	1990	Czarny Dunajec terrace	8500	778.0	3572.0	9.0	2987.0	80.0	496.0	Tatra series — Middle Triasic, brecciated dolomites and limestones	3218–3572
Biały Dunajec PAN-1 (21)	1989	Biały Dunajec terrace	10500	685.0	2394.0	5.0	2108.0	12.0	269.0	carbonate Eocene — conglomerates Tatra series — Middle Triasic, dolomitic limestones, dolomites and marly limestones	2117–2394
Banska IG-1 (22)	1981	Biały Dunajec over-inundation terrace	12000	679.0	5261.0	5.0	2555.5	96.0	2604.5	carbonate Eocene — limestones, marly limestones, conglomerates Tatra series — Upper Triasic, marly limestones, marls	2565–2683

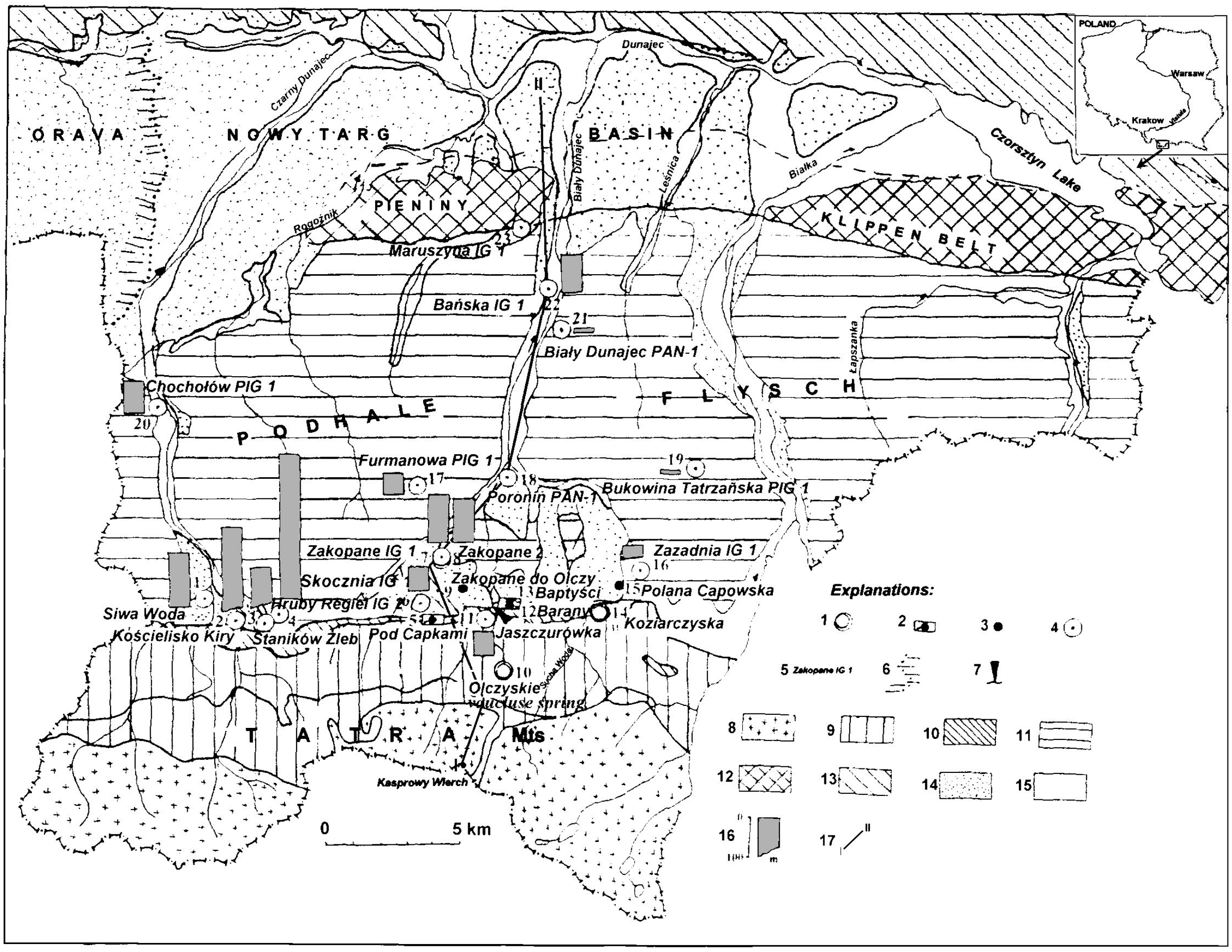


Fig. 4. Hydrogeological features of the geological units of Podhale and Tatra Mts.

1 — vaucluse spring, 2 — spring water intake, 3 — piezometric observation well, 4 — deep exploratory borehole, 5 — borehole, 6 — surface water divide between the Baltic Sea and Black Sea catchments, 7 — stream gauging station, 8 — crystalline basement, 9 — sedimentary facies, 10 — carbonate Eocene, 11 — Podhale Flysch, 12 — strata of the Pieniny Klippen Belt, 13 — Outer Carpathian Flysch, 14 — glaciofluvial sediments, 15 — alluvium of main river valleys, 16 — thickness of carbonate Eocene, 17 — geological cross section (see Fig. 9)

in recharging of artesian waters. Such an interpretation was supported by observations carried from 1976 to 1980 in both boreholes withdrawing the thermal waters of Antałówka.

Of the many exploratory-discharging wells drilled, only Zakopane IG 1 and Zakopane 2 were systematically monitored with respect to groundwater dynamics and chemical composition. Moreover, they are protected by the mining area of over 17 km^2 within which the other intakes are also located such as: the Skocznia IG 1 well, the intake of the Pod Capkami Spring, and the Barany and Baptyści springs in Jaszczurówka (Fig. 3). Observed correlations of water pressure in both exploited aquifers with the discharge of the Pod Capkami Spring, located over 1.5 km south-west of Antałówka, suggests the direct influence of meteoric recharge. The course of graphs clearly imitate the oscillation of monthly mean air temperature values as well as the sums of monthly atmospheric precipitation with culminations of discharge in summer and low groundwater flow within the period preceding the snowmelt (Małecka, 1984; Małecka and Murzynowski, 1989; Małecka and Małecki, 1998).

RESULTS OF MONITORING AND EXPERIMENTAL RESEARCH

The research concerned mainly the dynamics of the Pod Capkami Spring, discharging the carbonate Eocene aquifer, as well as observational and exploitational wells drilled around Zakopane.

The Pod Capkami Spring, recharging the water-supply of Zakopane, has long been an object of interest to local authorities. Various opinions regarding the lowering of the discharge of the spring appeared as oral communications and notes in hydrogeologic documentations. It was supposed that the lowering of discharge was caused by a local quarry, already then closed, or the building of the ski jump.

Stationary monitoring carried since 1972 showed that from 1976 the discharge of the spring oscillated around the long-term mean value (Fig. 5). Perceptible regression and subsequent vanishing of the discharge occurred in July 1976 and persisted for two months. In 1977 the spring appeared only periodically during the spring snowmelt or after heavy rain. It was then realised that the disappearing of the discharge could be ex-

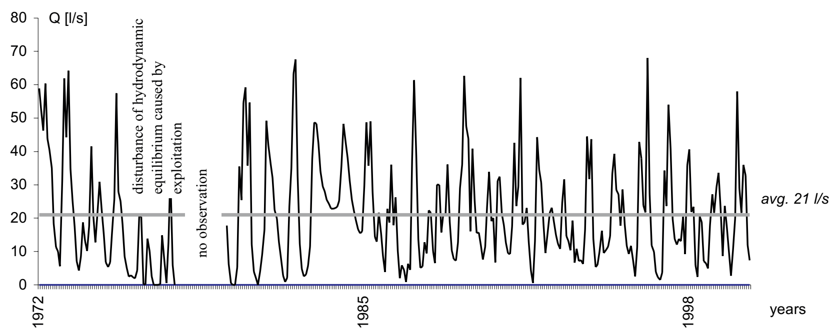


Fig. 5. Observed reaction of the Pod Capkami Spring after Zakopane 2 well pumping with free outflow

Table 2

List of hydrogeological points monitored during a pumping test with free outflow of Zakopane 2 well

Hydrogeological point		Altitude [m a. s. l]	Geological environment of groundwater occurrence	Distance from Zakopane 2 well [m]	Reaction to pumping Zakopane 2 well
Name (No. according to Fig. 4)	Character				
Zakopane 2 (8)	borehole	868.2	karst-fissural waters of carbonate Eocene	–	–
Zakopane IG 1 (7)	borehole	864.9	karst-fissural waters of Tatra series	80	instant reaction
Pod Capkami intake (5)	spring	907.5	contact of carbonate Eocene and Podhale Flysch	1587	reaction after 4 hours
Skocznia IG 1 Zakopane (6)	borehole	883.2	karst-fissural waters of Tatra series	1100	reaction after 3 hours
Zakopane to Olcza (9)	dug well	902.5	pore waters of Zakopane cone on Flysch	1350	reaction not detected
Olczyski Spring (10)	vaucluse spring	1040.0	karst-fissural waters of Tatra series	4050	no reaction
Olczyski Stream	stream at Tatra mouth	1053.5	surface waters	3900	no reaction
Barany Spring (12)	spring above Witkiewicz shrine	919.0	carbonate Eocene in the contact zone with Podhale Flysch — karst-fissural waters	2850	noticeable reaction after 24 hours
Baptystów Spring (13)	Spring below Witkiewicz shrine	915.0	carbonate Eocene in the contact zone with Podhale Flysch — karst-fissural waters	2775	weak reaction after 24 hours
Koziarczyska Spring (14)	vaucluse spring	945.0	carbonate Eocene in the contact zone with Podhale Flysch	6450	no reaction
Capowska clearing (15)	dug well	922.5	pore waters of Sucha Woda cone on flysch	7100	no reaction
Zazadnia IG 1 Małe Ciche (16)	borehole	855.2	karst-fissural waters of carbonate Eocene	7850	test results to not justify any conclusions

plained neither by natural factors nor by the disused quarry. Moreover, a clear instability of the spring hydrogeologic regime was observed while pumping tests of the Zakopane 2 well were performed (Małecka *et al*., 1979). A restriction of the discharge of Antałówka thermal water up to the permissible volume of extraction renewed the activity of the spring. It was significant that the year 1980 was characterised by the highest precipitations for fifty years (Fig. 6). The Kasprowy Wierch Mountain (Fig. 4) saw a precipitation of 2367 mm, as much as 558 mm falling in July. After this period the discharge of the spring returned to normal while the Antałówka remains a valuable experimental field for research.

Subsequent questions were: 1 — the similar reaction of both wells to climate despite one exploiting water from the Tatra succession and, the other from carbonate Eocene, at depths varying by about 500 m, and 2 — the degree of influence of Antałówka thermal water exploitation on adjacent areas.

To solve the first problem, hydrogeological calculations were performed based on long-term observations in the Zakopane IG 1 and Zakopane 2 wells, to determine the hydrogeological parameters of the strata exploited. Two working assumptions were made:

— the Antałówka wells draw from two independent water-bearing formations, and

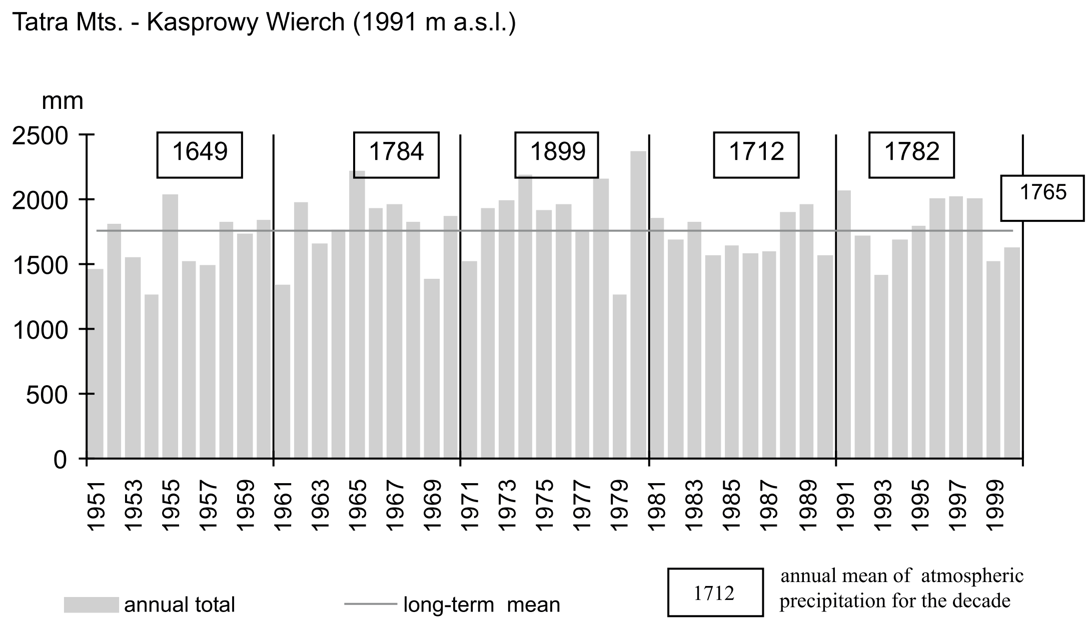


Fig. 6. Annual and decade means of atmospheric precipitation

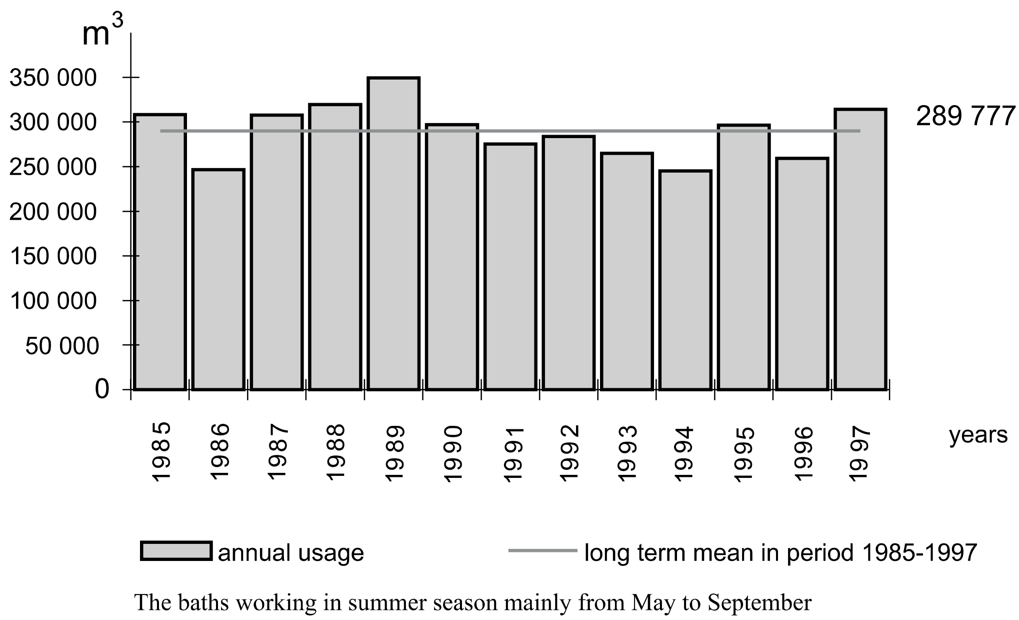


Fig. 7. Thermal water discharge to the Antałówka baths in Zakopane

— the two aquifers are hydraulically connected.

Calculations directed by Professor T Macioszczyk (Małecka and Murzynowski, 1989) were consistent with hydraulic connection between the aquifers exploited within Antałówka.

The second question, regarding the range of influence of the exploited Antałówka thermal waters, required an experimental approach. The hydraulic equilibrium was disturbed by exploiting the Zakopane 2 well with free outflow, while observation points were monitored. These experimental tests continued uninterruptedly for 5 days, and included monitoring of 12 hydrogeological points (Table 2). Reaction to free outflow from the Zakopane 2 well was instantly registered in the Zakopane IG 1 well. The Skocznia IG 1 well also reacted, withdrawing fissure-karst waters from Tatra facies rocks, then the Pod Capkami Spring draining carbonate Eocene outcrops. After one day, the influence of pumping was observed in the Jaszczurówka dislocation springs 3 km from Antałówka. In other test points no changes caused by exploitation of the Zakopane 2 well were observed. In the Olczyskie vaucluse spring, in the Olczyski Stream monitored in the Jaszczurówka hydrometric section and in dug wells exploiting ground waters in fluvioglacial cones at the foot of the Tatra, waters reacted only to precipitation. The experiment was stopped due to rapid

Table 3

Characteristics of thermal waters at Antałówka, Zakopane

Name and designation of well	Zakopane IG 1 well *	Zakopane 2 **	
Approved admissible volume of extraction from the well	Q — 50 m^3/h S — 50 m T — 36°C	Q — 80 m^3/h S — 20 m T — 26°C	
Hydrogeochemical type of water n = 76	HCO_3-SO_4-Ca-Mg	HCO_3-Ca-Mg	
H_2S content [mg/dm^3]	mean	1.45	0.92
	max	2.61	1.49
	min	0.89	0.32
Total dissolved solids [mg/dm^3]	mean	353	321
	standard deviation	20.60	14.43
	inconstancy factor	0.058	0.045
Mean water temperature at well-head in1976–1980 [°C]	mean	35.5	26.2
	max	35.8	26.5
	min	35.2	25.9

stationary investigation carried out from: * — 1996, ** — 1976; n — number of samples; Q — discharge; S — depression

decrease of discharge of the Pod Capkami Spring which recharges the water-supply of Zakopane. Thus, extending the duration of pumping or range of exploitation of both Antałówka thermal wells would likely expand such influence outside the mining area (Fig. 3).

This limited experiment confirmed the existence of dynamic connections between the aquifers of the carbonate Eocene and Tatra facies within the upper multi-aquifer succession of the southern flank of Podhale artesian basin. Further evidence was provided by a well Skocznia IG 1 bored in 1986 at the foot of the Zakopane ski jump (Fig. 3, Table 1). During exploitation of this well, both Antałówka intakes reacted first. The Pod Capkami Spring, despite its proximity to the well, reacted only after 5 hours. Its output was lowered proportionally to the water withdrawn from the well Skocznia IG 1 (Małecka and Murzynowski, 1989).

Thus, excessive exploitation of any well drilled in the area of Zakopane and withdrawing water from sub-flysch aquifers would disturb the hydrological equilibrium. All the springs supplying drinking water for Zakopane (Pod Capkami, Barany, Baptyści) react to the exploitation of the Skocznia IG 1 well and the Antałówka thermal wells.

These findings gave the local authorities grounds to prohibit any further drilling around Zakopane. Current plans to construct new swimming pools and balneologic baths on Antałówka indeed necessitated decrease of admissible water extraction from the Skocznia IG 1 well from 22.7 to 10 m^3/h.

CURRENT UTILISATION OF GROUNDWATERS

Groundwater in the sub-flysch aquifers of the southern flank of the Podhale artesian basin are utilised in two ways: 1 — as a local source of drinking water, for instance: the Hruby Regiel IG 1, Staników Żleb, Skocznia IG 1 wells, and 2 — as thermal waters at Antałówka, used in summer as a source of water for swimming pools. Usage of these waters is relatively low and amounts to about 300 000 m^3 per year (Fig. 7). During exploitation, an hour's intake of water ensuring proper function of the baths amounts to 70 m^3/h, the admissible volume of water extraction from the well being 130 m^3/h (Małecka and Małecki, unpub.). Thus the thermal waters of Antałówka are not fully utilised, although they were discovered almost 40 years ago.

The Balneologic Institute in 1964 stated that water from the Zakopane IG 1 well are weakly mineralised thermal waters containing H_2S, fitting curative purposes such as:

— curative baths;

— healing rheumatoid diseases;

— limb rehabilitation, while the H_2S content might ameliorate skin diseases.

Based on this statement the Ministry of Health and Social Welfare approved thermal waters of the Zakopane IG 1 well as curative. In the Polish Monitor no. 29 from 1974, a statement regarding "thermal waters containing H_2S from the resources of Zakopane" can be found; a similar definition was extended to water from the Zakopane 2 well.

Because these waters have not been utilised for balneologic purposes, in the Decree of the Cabinet from 1994 they were passed over at the register of curative waters. They were qualified as thermal waters only and this is their legal status today. In 1995, in connection with the planned construction of a large complex of balneological baths, the "Polskie Tatry"corporation received a concession regarding "withdrawing thermal waters from Eocene and Domerian resources located in Zakopane and

Table 4

Chemical composition of water from the Bańska IG 1 well

Probing depth [m b.g.l.]	Date	pH	Number of analyses	Chemical composition expressed by Kurlov formula *M* [mg/dm³;] ions [% meq]
3094–3224	11.04.81	7.6	1	$M_{2814}\dfrac{SO_4^{48}Cl^{39}HCO_3^{13}}{Na^{61}Ca^{24}K^{8}Mg^{7}}$
2960–2770	25.04.81 30.04.81	7.5	2	$M_{2948}\dfrac{SO_4^{46}Cl^{39}HCO_3^{15}}{Na^{59}Ca^{27}Mg^{9}K^{5}}T^{51}$
2565–2683 range of exploited depth	9.06.81–29.06.81*	7.8	6	$M_{3027}\dfrac{SO_4^{44}Cl^{42}HCO_3^{14}}{Na^{55}Ca^{28}Mg^{11}K^{6}}T^{66}$
	26.06.81**	7.6	1	$M_{3022}\dfrac{SO_4^{47}Cl^{37}HCO_3^{16}}{Na^{59}Ca^{30}Mg^{10}K^{1}}T^{72}$
	18.03.83–30.06.83	7.3	4	$M_{3041}\dfrac{SO_4^{44}Cl^{40}HCO_3^{16}}{Na^{56}Ca^{27}Mg^{11}K^{6}}T^{69}$
	21.10.96***	7.0	1	$M_{2523}\dfrac{SO_4^{48}Cl^{37}HCO_3^{15}}{Na^{58}Ca^{29}Mg^{10}K^{3}}T^{76}$
	15.03.97*** 22.03.97	6.7	2	$M_{2605}\dfrac{SO_4^{49}Cl^{37}HCO_3^{14}}{Na^{60}Ca^{28}Mg^{9}K^{3}}$

* — analyses from pumping-tests; ** — pumping with free outflow and discharge of 60m³/h; *** — probing during hydrodynamic tests to "Hydrogeological documentation of Podhale basin thermal waters" (Chowaniec *et al*., 1997); *M* = TDS — total dissolved solids)

the territory of its commune within the Zakopane mining area in quantites up to the approved admissible volume of extraction". The concession was extended to 2008 on the same conditions. The effort by the "Polskie Tatry" corporation to manage these water resources should benefit the town.

The approved admissible volume of extraction, chemical stability and temperature of the water as well as its content of H_2S (Table 3) show a possibility to obtain renewed registration of these waters as curative. This would considerably raise the rank of Zakopane as a spa.

SUB-FLYSCH AQUIFERS OF CENTRAL AND NORTHERN PART OF THE BASIN

A turning point in understanding the hydrogeology of the entire Podhale artesian basin occurred after drilling a deep exploratory borehole — Bańska IG 1, 12 km north of the Tatra Mountains (Fig. 4). The borehole was conceived by J. Sikora and J. Sokołowski, geologists from the Polish Geological Institute. Determination of the geological structure of the transition zone between the inner and outer Carpathians, analysis of reservoir characters of the rocks penetrated, and prospects for oil- and gas-bearing deposits were the main objectives of the borehole. The drilling started in June 1979 and was finished in January 1981 at a depth of 5261 m. Associated research included determination of reservoir characters and the possibilities of thermal water storage. Eventually, carbonate Eocene strata (96 m thick) and the upper parts of the Middle Triassic marly limestones and marls at a depth of 2565–2683 m were chosen for thermal water extraction. A pumping test with free outflow produced thermal water at a temperature of 72°C, with total dissolved solids of 3 g/dm³ and discharge of 60 m³/h (Table 4).

Considering the stagnant groundwater reservoir, isolated by a thick cover of flysch sediments, and therefore a geologically long residence time of water in the aquifer and its trend to achieve geochemical equilibrium with the host rock, the value of total dissolved solids in the water should be much higher than that observed. Moreover, within the flysch deposits of the Outer Carpathians, thermal waters are usually saline (Dowgiałło, 1994). Thus, flow of the Podhale basin thermal waters, consistent with the northward dip of the Tatra facies, should change to E–W in the near-Pieniny zone where the water spreads fanwise and flows beyond the national border (Małecka, 1992).

The impermeability of the contact zone between Podhale Flysch and the Pieniny Clippen Belt was revealed during mapping in Podhale (Macioszczyk, unpubl.; Małecka, 1974). Drilling at Maruszyna (Fig. 4) also showed that the Pieniny Mountains provide a natural impermeable barrier making migration of the deep circulating water of the Podhale artesian ba-

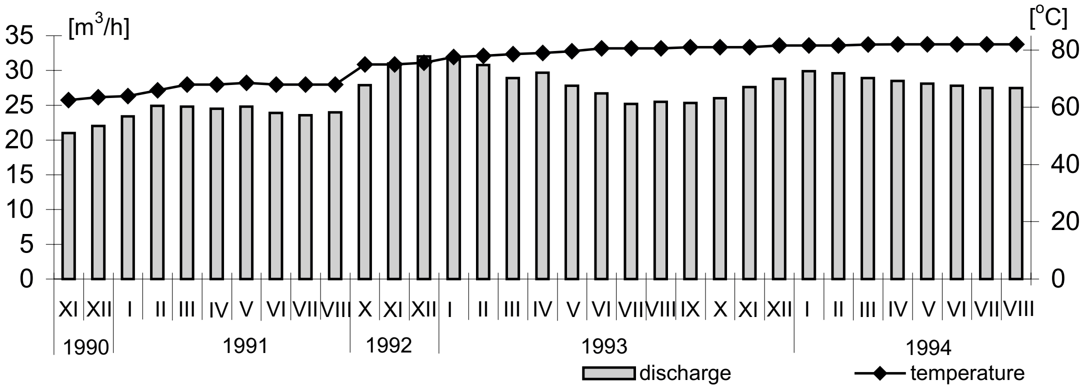


Fig. 8. The results of Bańska IG 1 well monitoring (data adopted from Kępińska, 1995)

sin to the north impossible. The drilling at Maruszyna, completed in 1981, penetrated a few strongly folded and brecciated rock units and their Upper Cretaceous cover (Birkenmajer, 1986). The vertical bedding strongly suggests that a similar geological structure may occur to a depth of 5 km at least.

UTILISATION OF THERMAL ENERGY FOR HEATING

The most important role, scientifically and economically, has been played by experimental research regarding geothermal energy as a source of clean raw energy.

Concept and project studies led to the creation in 1989–1991 of the Experimental Geothermal Works Bańska — Biały Dunajec, initiating an installation supplying heat to nearby communities (Sokołowski, 1984, 1985, 1989; Nowicki *et al*., 1985; Sokołowski and Poprawa, 1985). This stage of the research was realised by the Centre of Basic Problems of Management of Mineral Resources and Energy of the Polish Academy of Science, and led by Professor J. Sokołowski. The experiment comprised sending thermal waters through a system of pipelines from the Bańska IG 1 well, and pumping them into the Biały Dunajec PAN-1 well with the simultaneous collection of heat.

As the needs of local communities for geothermal heating increased the Geotermia Podhalańska S.A. corporation was founded. In 1995 the Centre of Basic Problems of Management of Mineral Resources and Energy was replaced by the Geothermal Laboratory. Research regarding the extraction and management of geothermal energy within Podhale was focussed on:

— construction of a central heating system, which is expected to replace traditional organic fuels currently used,

— extension of its utilisation in the drying and greenhouse industries,

— fish breeding,

— recreation and balneology (Kępińska, 1996).

The Geothermal Laboratory plays also an important role as a centre of ecological education where a working geothermal system and the geothermal resources of the Podhale basin may be monitored.

An important question is the degree to which the extraction of thermal waters from such well-couplets as Bańska IG 1 and Biały Dunajec PAN-1 may influence the natural groundwater circulation and to what degree the groundwater chemical composition and temperature will be modified. According to Kępińska (1997) these effects will reflect mainly the anisotropy and tectonics of the massif around the exploited wells. Determination of the scale of such changes will require systematic monitoring.

Observations carried out on the Bańska IG 1 well indicated that, during groundwater extraction with a discharge of 20–30 m^3/h, the water temperature at the well-head gradually rose from about 63°C in 1990 to 82°C in 1994 (Fig. 8). Research showed a positive thermal anomaly around the well-couplets with its maximum near to the Biały Dunajec PAN-1 well, the water temperature here reaching 90°C (Kępińska, 1997). Deep faults, mainly of Upper Cretaceous and Neogene age, help determine the hydrogeological and thermal structure of this region. The importance of such tectonics within the deepest part of the Podhale basin is also suggested by the "gliczarowska calc-sinter" described by Halicki and Lilpop (1932), and the occurrence of a spring with one of the largest discharges, exploited today to serve the needs of local communities (Małecka, 1973).

CURRENT STAGE OF RECOGNITION OF PODHALE ARTESIAN BASIN

Understanding of the geological and hydrogeological structure of the Podhale basin was further enhanced by exploration and exploitation wells drilled in 1990 and 1991 at Furmanowa, Chochołów and Bukowina Tatrzańska. These showed an increase in the thickness of flysch facies penetrated on moving away from the Tatra Mountains, from a few metres thickness at the foot of the massif to 2000 m, and even 3000 m in the north-western part of the basin, in the vicinity of Bańska and Chochołów (Fig. 4, boreholes no. 20–22). The carbonate Eocene strata show a different pattern. Their local thickness variation, determined by the varied relief of the pre-Palaeogene

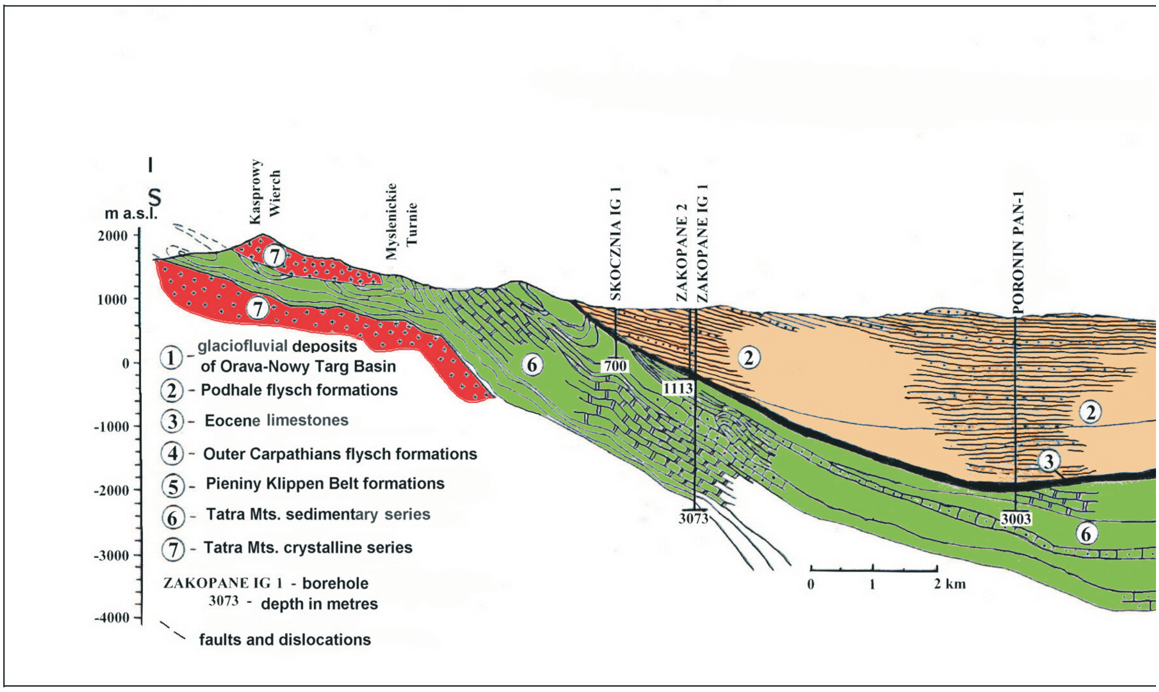
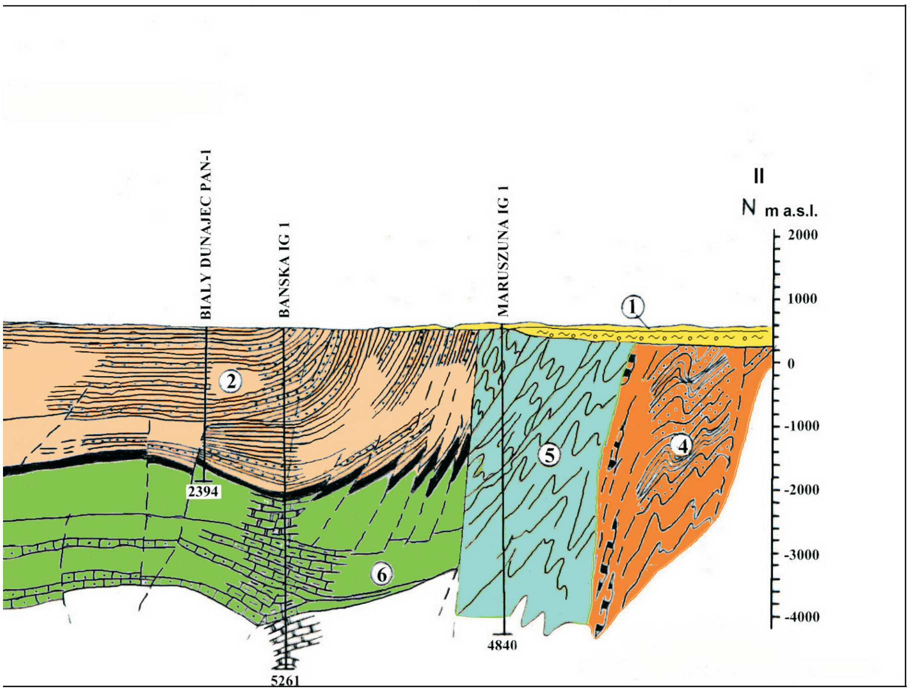


Fig. 9. Geological cross section

surface and the sedimentation style, reach a few tens of metres in the central part of the basin and exceed 360 m within the watershed zone between the groundwater drainage area of the Czarny and Biały Dunajec, near the Hruby Regiel IG 1 well (Table 1, Fig. 4). As previously mentioned, the carbonate Eocene, from a hydrogeological point of view, reveals many similarities with Mesozoic deposits of Tatra facies. Both these water-bearing formations are exploited in a few wells. The best example is the system of wells monitored by the Geothermal Laboratory of the Polish Academy of Sciences at Biały Dunajec. The results of these observations were most fully described by Kępińska (1997, 2001). She prepared a geological-geothermal model of the Podhale basin, taking into account successive stages if its palaeodynamic development. Using mineralogical-thermal and geochemical test methods she reached the conclusion that "...Podhale geothermal system, since its thermal maximum, has significantly cooled...", and the process of filling fissures and fractures with secondary minerals (mainly calcite) has decreased the permeability of reservoir rocks.

Useful information concerning the occurrence and extraction possibilities of the thermal waters of the Podhale artesian basin were provided by the Carpathian Branch of the Polish Geological Institute and Geotermia Podhalańska S.A. in 1996/1997. The results were described by Chowaniec *et al.* (unpubl.), and showed the chemical stability of waters from the Bańska IG 1 well.

Records collected in 1981–1997 show that, according to the Balneoprojekt in Warsaw, the existance of hyperthermal water belonging to SO_4-Cl-Na-Mg hydrogeochemical type containing fluorite, iron and boron. The bicarbonate ions which, dominate the waters of the southern flank of the Podhale artesian basin, do not occur in Bańska IG 1 water in concentrations affecting the hydrogeochemistry of the water, and the total of dissolved solids is about seven times higher then those in the southern part of the basin (Table 4). The hydrogeochemistry of the water depends on the distance from the recharge area and the permeability of fissure-karst systems responsible for the velocity of groundwater flow. Meteoric water, according to the dip of water-bearing beds under the flysch deposits of Podhale (Fig. 9), move northward and spread fanwise to the east and west beyond the national border where they meet the aquifuge screen of the Pieniny Klippen Belt. Thus, on moving away from the Tatra Mts. the total dissolved solids in the water gradually increases and their chemistry changes (Fig. 10). According to Witczak (Chowaniec *et al*., unpubl.), in the near geological past, the Podhale artesian basin was filled by saline waters, which have today undergone substantial dilution by meteoric water. As previously mentioned, the degree of meteoric water influx into the reservoir depends on the velocity of infiltration and the permeability of the water-bearing rocks. Within the southern flank of the basin this process is most intensive because of fast groundwater exchange. As the distance from the recharge area (the Tatra Mts.), increases to the north the velocity of groundwater flow decreases considerably. This is shown by spatial changes in both the chemical and isotopic composition of the waters (Nowicki, unpubl.; Chowaniec *et al*., unpubl.; Małecka and Nowicki, 2002). These are young waters, the underground flow and exchange of which is facilitated by the system of faults, fissures and karst caverns. The youngest waters, with a considerable tritium content, evidence of a modern re-



Kasprowy Wierch–Maruszyna after Małecka and Nowicki, 2002 (see location on Fig. 4)

charge component, were found within southern flank of the basin (the Staników Żleb, Hruby Regiel IG 2, Skocznia IG 1, Zakopane IG 1, Zkopane 2 and Zazadnia IG 1 wells) as well as in the Furmanowa PIG 1 well located 4.7 km away from the Tatra Mts. The older waters, presumably not exceeding Holocene in age, occur within the central and northern part of the basin.

CONCLUSIONS

Extensive research concerning groundwater hydrodynamics, age, temperature and ionic composition demonstrate factors governing the groundwaters of the Podhale artesian basin:

— J. Gołąb's early model for the origin of Jaszczurówka Therma, introduced in1950's, was substantially correct.

— The hypothesis that Tatra sedimentary facies dip below flysch strata, and meteoric water infiltres through a system of fissures and karst caverns to significant depths, led J. Gołąb and J. Sokołowski to test this model by means of exploratory boreholes. This led to the discovery of artesian thermal waters within the Tatra foreland in 1963.

— The fundamental role of carbonate Eocene rocks in the hydrogeology of the Podhale artesian basin results from its superposition on Mesozoic bedrock as well as from its covering by shale-sandstone flysch strata behaving as an impermeable isolation cap. Both the carbonate Eocene and Mesozoic Tatra successions constitute a single thermal water-bearing horizon exploited nowadays by the Bańska–Biały Dunajec well couplet as a source of clean energy and for seasonal baths. The organodetrital limestones, conglomerates and dolomites of the carbonate Eocene offer most prospects for utilisation of geothermal energy in the Podhale basin.

— Monitoring and experimental research show that the entire Tatra massif is involved in recharging of sub-flysch water-bearing strata. They showed also a meteoric origin for the groundwater and the existence of hydrodynamic links between aquifers of the carbonate Eocene and Tatra facies within the Podhale artesian basin. Moreover, overexploitation at any well around Zakopane may perturb the natural equilibrium state of sub-flysch aquifers.

— The thermal waters of the Podhale basin show features typical of the leaching of underground rock reservoirs (filled by saline water in the geological past) by meteoric water. Varying intensity of this reservoir leaching by meteoric water, as well as a decrease in underground flow velocity from the zone of recharge towards the axis of maximal subsidence of the basin on the Bańska–Chochołów line, is reflected by: 1 — the rise of total dissolved solids from 200–400 mg/dm^3 through 1000 to about 3000 mg/dm^3; 2 — the change of their hydrogeochemical types from HCO^3-Ca-Mg through HCO^3-SO^4-Ca-Mg to SO^4-Cl-Na-Ca within the central part of the basin; 3 — a gradual decrease of the content of bicarbonates.

— Spatial changes in the chemical composition of the groundwater of the Podhale artesian basin are closely related to their age estimated by isotopic study, helping to define the regional hydrogeological structure. The youngest groundwaters,

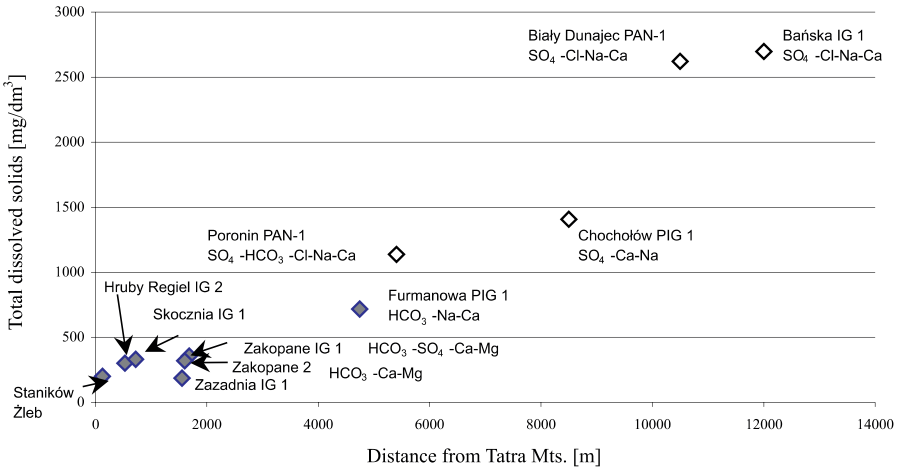


Fig. 10. Dissolved solids and hydrogeochemical types of groundwaters of the Podhale artesian basin in the boreholes studied

containing tritium, occur along the southern flank of the basin and are of freshwater type. The older groundwater, of Holocene age, occurs mostly in the central and northern parts of the basin, contains more dissolved solids, over 1000 mg/dm^3, and therefore comprise mineral waters.

— Penetration of Tatra foreland through by a number of boreholes has provided indispensable data concerning the use of thermal water for recreational purposes as well as for optimal utilisation of the geothermal resources of the basin as a source of clean, environment-friendly energy.

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