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Groundwater ages and altitudes of recharge areas in the Polish Tatra Mts. as determined from ^{3}H, δ^{18}O and δ^{2}H data

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Large and medium karstic springs in the Polish Tatra Mts. occasionally sampled during low flows exhibited little scatter of stable isotope composition and distinct differences between particular sampling sites. For extreme stable isotope values of four springs, the recharge altitudes were estimated by making use of topographic and geological maps. The altitude effect found in that way served for determining the recharge altitudes of other sampled sites. The altitude-effect gradients found in that way are –0.21‰/100 m and –1.45‰/100 m for δ^{18}O and δ^{2}H, respectively. In general, large karstic springs (exsurgents) have the highest recharge altitudes whereas medium spring and deep wells are characterized by much lower altitudes. Tritium data interpreted with the aid of lumped parameter models yielded mean ages of *ca*. 3 years for low flows in large karstic springs, *ca*. 10 years for medium springs, and 50 to 100 years for deep wells, all with very wide age distributions. For four deep wells, the regional hydraulic conductivity estimated from tritium ages (0.8×10^{-6} m/s) is about 20 times lower than the geometric mean found from pumping tests (17×10^{-6} m/s) suggesting the existence of obstacles to regional flow.

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Key words: Tatra Mts., groundwater, environmental isotopes, altitude effect, tritium ages.

INTRODUCTION

The Tatra Mts. represent the highest part of the Western Carpathians with its highest peak Gerlach (2655 m) in Slovakia. They are built of granites, metamorphic and sedimentary rocks. Water bearing sedimentary formations are represented by High Tatra unit, Sub-Tatra unit, and carbonate Eocene unit (Fig. 1). High Tatra unit is mainly built of Jurassic sandstones, limestones and marls, Sub-Tatra unit is mainly built of Triassic sandstones, limestones and dolomites, Jurassic sandstones, limestones and marls, and carbonate Eocene unit is mainly represented by limestones and dolomites (Fig. 2). All these formations dip to the north, where thick flysh sediments cover them in the Podhale Basin. The general flow direction is also to the north, up to an impermeable obstacle of the Pieniny Klippen Belt (beyond Fig. 1), which divides the flow, directing one component to south-west and the other to south-east, where they omit the Tatra Mts. elevations and discharge in the Danube watershed.

There are numerous springs and several deep wells within the investigated area which covers the Zakopane aquifer with freshwaters in its initial part and thermal waters in deeper parts extending to the thermal system of the Podhale Basin (Figs. 1 and 2). The northern boundary of the Zakopane aquifer was arbitrarily assumed by Kleczkowski ed. (1990), the western and eastern boundaries were chosen along the state boundary whereas the southern boundary is defined by outcrops of carbonate formations. The largest springs and wells were sporadically sampled for ^{3}H, δ^{18}O and δ^{2}H analyses under different projects in the period of 1977–2001. In most cases, springs were sampled only during low flows. All the isotope analyses were performed in the laboratory of the Faculty of Physics and Applied Computer Science, AGH-UST in Cracow by making use of well established analytical procedures. Early stable isotope data are given in relation to the SMOW standard whereas later data in relation to V-SMOW, which for practical purposes is equal to the SMOW (Coplen, 1996). Tritium concentrations are given in tritium units (T.U.), where 1 T.U. = 1 tritium atom per 10^{-18} atoms of common hydrogen.

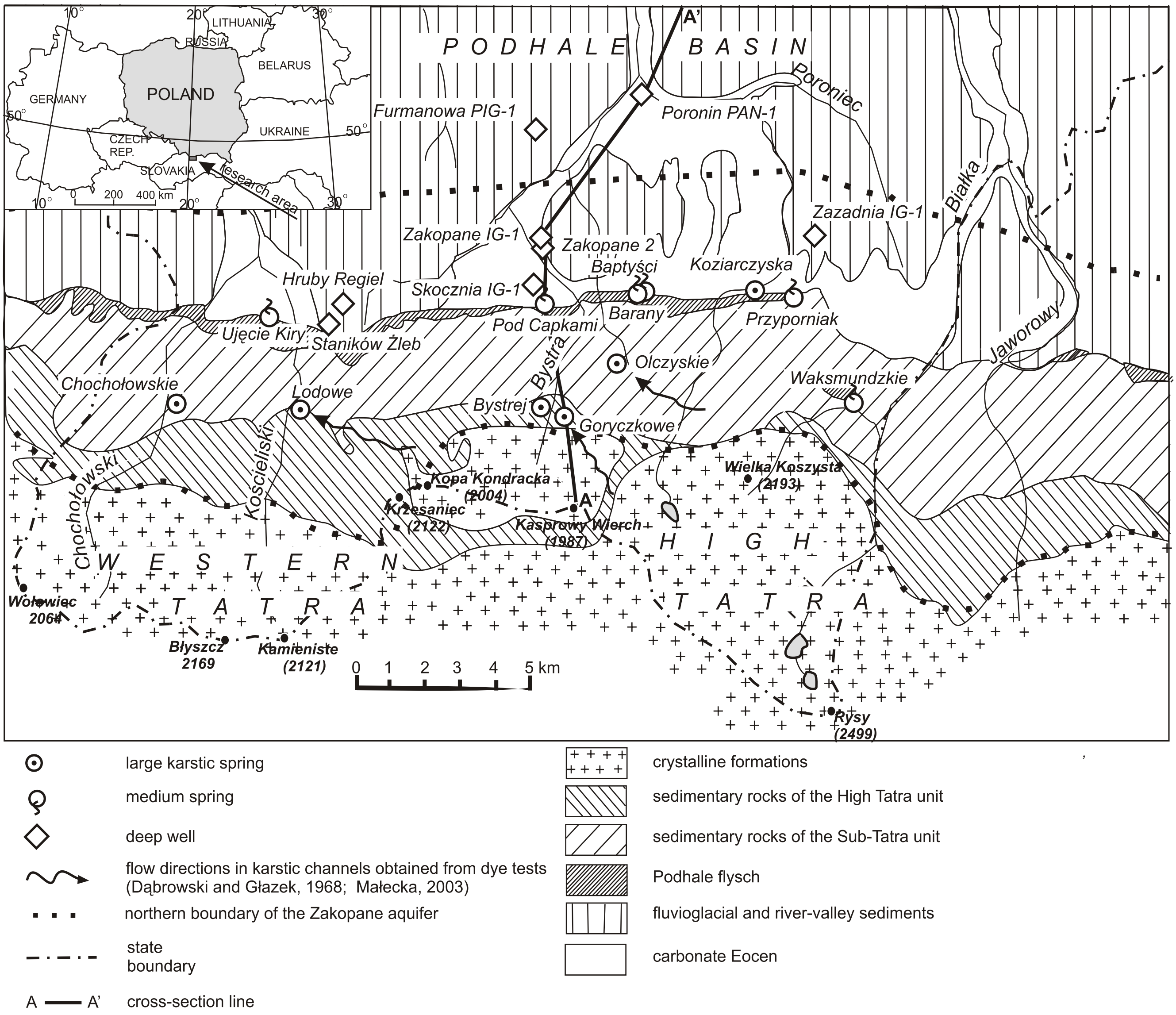

Fig. 1. Simplified geological map of the Polish Tatra Mts. and the positions of sampling sites

The aim of the present work is to summarize all available environmental isotope data and interpret them in terms of recharge altitudes and water ages, because in an earlier work related to the Podhale Basin (Małecka and Nowicki, 2002) only selected isotope results were given, with an estimate of tritium age performed only for the Zakopane IG-1 well in an approximate way.

ISOTOPE DATA

The environmental isotope data of large springs, medium springs and deep wells are summarized in Tables 1, 2 and 3, respectively. The results are practically free of the seasonal isotope effect because samples were taken during low flow conditions and the mean tritium ages are not less than *ca*. 4 years, as discussed further. In such cases, the seasonal effects are strongly damped and immeasurable in outflows.

The stable isotope data of sampled sites lie generally above the World Meteoric Water Line (WMWL) and above the precipitation line determined by Różański and Duliński (1988) for the Ornak Alp in the Kościeliska Valley from two years observations, but in agreement with surface outflows reported by these authors. Therefore, their precipitation given by Equation [1] cannot be regarded as representative for a long term recharge of groundwater. An attempt to explain the position of all data above the WMWL was given by mentioned authors.

$$\delta^2H = (8.1 \pm 0.2)\ \delta^{18}O + (13.0 \pm 2.1) \qquad [1]$$

The groundwater line shown in Figure 3 differs from Equation [1] only by the value of the free term equal to 14.5‰. Isotope contents of thermal waters do not exhibit any shift from the general line, which should be expected for enhanced isotopic exchange of oxygen with carbonate minerals in elevated temperatures (e.g., Gat and Gonfiantini, 1981).

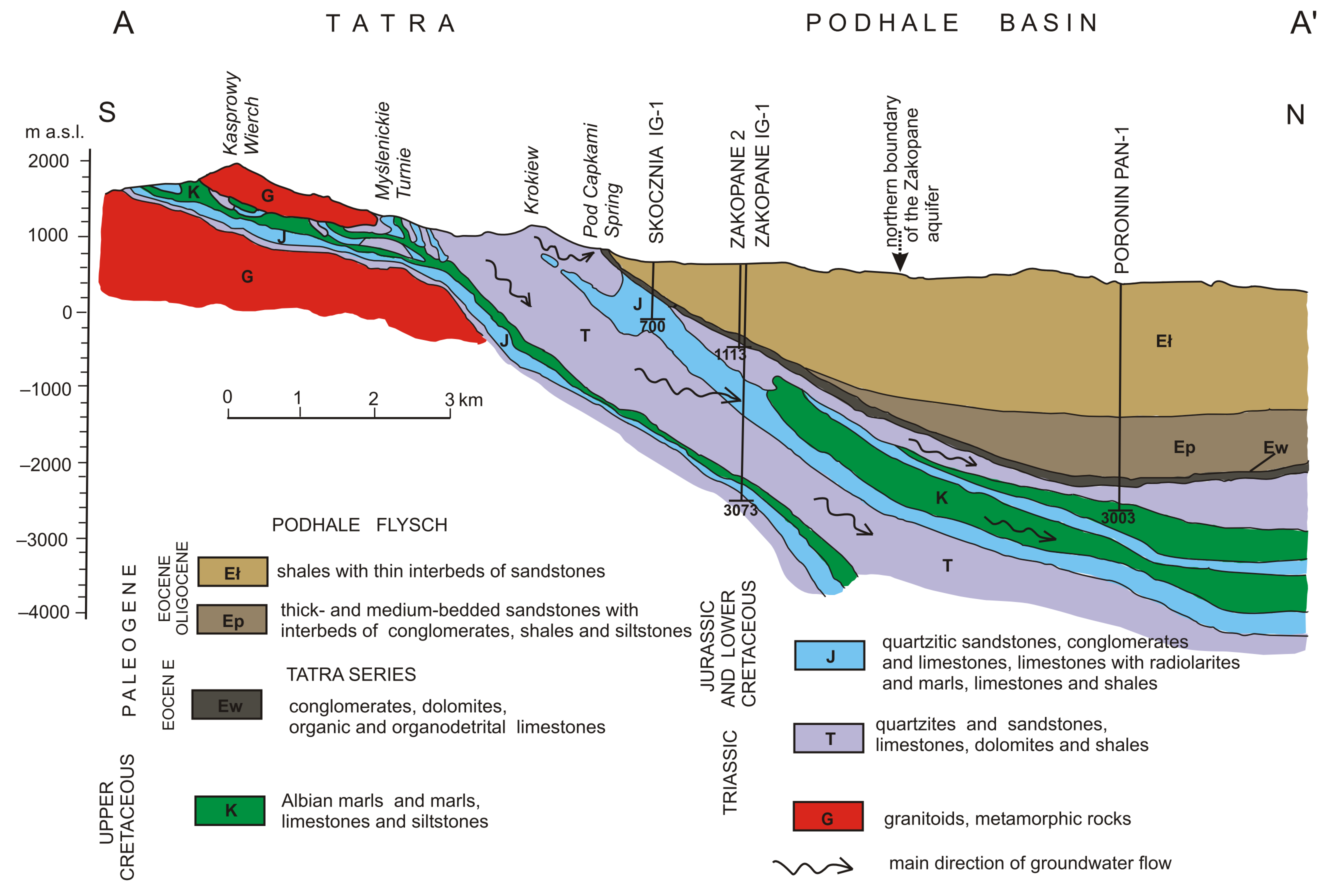

Fig. 2. Simplified geological cross-section A–A'

The stable isotope data of each sampling site are little scattered, as seen in Tables 1 to 3, which means that they can be regarded as fairly representative for conditions of low flows, whereas the median values of particular sites are distinctly differentiated (Fig. 3).

The tritium series are in general incomplete and too short for unique age interpretation. Spring and well waters exhibit in most cases similar pattern, with high tritium contents in late seventies and eighties and with *ca*. 10 T.U. at the beginning of the new century.

ALTITUDES OF RECHARGE AREAS

The differences between median δ-values of particular sampling sites can be related to the well known altitude effect (e.g., Gat and Gonfiantini, 1981). In order to determine quantitatively that effect, the altitudes of recharge areas of springs with extreme δ-values were estimated on the basis of the altitudes of outflows, and the analysis of geologic and morphologic maps, which constrained the possible ranges of the sought values as indicated by uncertainties shown in Table 4. The linear relationship was assumed for other sampled sites having intermediate δ-values with altitude uncertainties resulting mainly from the uncertainties estimated for the extreme values. The results of that interpretation are represented by Equations [2] and [3], and shown in Figures 4 and 5 for δ^{18}O and δ^{2}H, respectively (also see Table 4).

$$h_{18}\ (\text{m a.s.l.}) = -445.3 \times \delta^{18}\text{O} + 3704 \qquad [2]$$

$$h_{2}\ (\text{m a.s.l.}) = -69.1 \times \delta^{2}\text{H} + 4054 \qquad [3]$$

All the large karstic springs are in general characterized by the highest altitudes of recharge areas, whereas deep wells and some medium springs have their recharge areas at the lowest altitudes, with the exception of the Zazadnia well, which is situated in the eastern part of the investigated area and recharged at the altitude comparable with some large springs.

TRITIUM AGES

Lumped parameter models (Małoszewski and Zuber, 1982; Zuber, 1986) were used to interpret tritium data with the aid of the *PCflow* program (Małoszewski and Zuber, 1996), whenever the records were sufficiently long for a reliable modelling. When considering ages obtainable from tracer data, it is necessary to remember that in fissured rocks the movement of any tracer is delayed in relation to the movement of mobile water due to the molecular exchange of mobile water and tracers in

Table 1

Isotope data of large springs and their altitudes

Name Code	Altitude [m a.s.l.]	Date	$\delta^{18}O_{V\text{-}SMOW}$ [‰]	$\delta^{2}H_{V\text{-}SMOW}$ [‰]	Tritium [T.U.]
Bystrej BY	1160	14.07.77	n.m.	n.m.	103±4
		15.12.86	–11.86	–79.9	42.9±1.9
		27.08.87	–12.22	–81.9	33.7±1.6
		13.12.87	–11.80	–81.9	n.m.
		28.06.01	–11.92	–82.3	11.6±0.8
		Median	–11.89 0.11	–81.4 0.6	–
Goryczkowe GO	1176	15.12.86	–11.51	–79.6	44.3±2.0
		27.08.87	–11.92	–81.9	28.3±1.4
		13.12.87	–12.01	–82.5	n.m.
		28.06.01	–11.72	–81.2	11.4±0.7
		Median	–11.82 0.13	–81.55 0.7	–
Olczyskie OL	1042	14.07.77	n.m.	n.m.	104±4
		11.12.86	–11.40	–75.6	41.8±1.9
		27.08.87	–11.74	–79.7	30.6±1.5
		13.12.87	–11.36	–80.8	n.m.
		28.06.01	–11.48	–80.0	13.0±0.7
		Median	–11.42 0.10	–79.85 1.3	–
Chochołowskie CH	974	09.07.77	–11.7	–81.5	103±4
		31.05.85	–11.66	–75.6	n.m.
		06.02.85	–11.42	–77.0	42.6±2.0
		27.08.87	–11.87	–81.2	27.5±1.3
		03.08.88	n.m.	n.m.	25.1±1.5
		28.06.01	–11.30	–78.0	11.6±0.8
		Median	–11.66 0.11	–78.0 1.2	–
Lodowe LO	974	15.10.84	–11.17	–73.8	n.m.
		31.05.85	–11.66	–75.6	n.m.
		01.02.85	–11.50	–77.2	43.2±2.0
		31.07.85	–11.29	–74.8	n.m.
		27.08.87	–11.72	–79.8	29.6±1.5
		28.06.01	–11.41	–77.9	11.6±0.8
		Median	–11.45 0.11	–76.4 1.3	–
Koziarczyska KO	942	13.12.86	–11.39	–75.6	45.1±2.0
		26.08.87	–11.41	–77.5	33.9±1.6
		03.08.88	–11.32	–79.2	31.8±1.5
		22.08.01	–11.31	–77.5	12.9±0.7
		Median	–11.35 0.03	–77.5 0.9	–

n.m. — not measured

fissures with stagnant or quasi stagnant water and tracers in microporous rock matrix (Foster, 1975; Neretnieks, 1981; Sudicky and Frind, 1982). In large time and/or space scales, tracers are usually evenly distributed due to the molecular diffusion between fissures and microporous matrix. As a consequence, their transport along flow lines is as if it were taking place in the whole water volume, which means that tracer ages represent the total water content in the massif, i.e. both mobile water in fissures and stagnant (or *quasi* stagnant) water in the matrix. Therefore, the tracer age (i.e. the age of water determined by tracer method) differs by the delay factor (R_p) from the age of mobile water derived from Darcy's Law. The delay factor is in a good approximation equal to the ratio of total porosity to fissure porosity (Małoszewski and Zuber, 1985; Zuber and Motyka, 1994).

The longest record of tritium data exists for the Zakopane IG-1 well. However, for that well, it was not possible to fit any model to the whole record. Therefore, the dispersion model (DM) was fitted to the early data with an additional sought parameter (β_1) representing the fraction of tritium-free water. The

Table 2

Isotope data of medium springs and a shallow well, and their altitudes

Name Code	Altitude [m a.s.l.]	Date	$^{18}O_{V\text{-}SMOW}$ [‰]	$^{2}H_{V\text{-}SMOW}$ [‰]	Tritium [T.U.]
Waksmundzkie WA	1075	26.08.87	–11.34	–77.0	26.3±1.3
		12.12.87	–11.12	–78.2	n.m.
		23.06.01	–11.18	–76.9	12.8±0.7
		Median	–11.18 0.07	–77.0 0.4	–
Kiry KI	920	27.08.87	–10.76	–74.4	35.1±1.6
		12.12.87	–10.58	–74.7	n.m.
		28.06.01	–10.59	–72.9	13.5±0.9
		Median	–10.59 0.07	–74.4 0.6	–
Pod Capkami CA	915	11.12.86	–10.71	–73.1	37.8±1.7
		11.06.87	–10.86	–72.7	37.4±1.7
		26.08.87	–10.88	–73.8	34.6±1.7
		12.12.87	–10.85	–74.7	n.m.
		26.06.88	–10.87	–74.7	33.6±1.6
		19.06.01	–10.94	–75.1	12.6±0.7
		Median	–10.87 0.04	–74.25 0.6	–
Babtystów BAB	915	11.12.86	–11.27	–75.3	57.4±2.5
		11.06.87	–11.24	–76.6	47.7±2.1
		26.08.87	–11.00	–74.8	51.3±2.2
		03.08.88	–11.24	–77.8	47.8±2.1
		Median	–11.12 0.06	–75.95 0.8	–
Barany BAR	919	11.12.86	–11.27	–76.2	60.0±3.0
		27.08.87	–11.13	–75.5	51.3±2.3
		19.06.01	–10.79	–74.0	13.3±0.8
		Median	–11.13 0.16	–75.5 0.7	–
Staników Żleb ST, Well, 95–110 m	967	11.06.87	–11.20	–73.6	38.0 1.7
		24.06.01	–10.90	–75.9	13.2 0.9
		Median	–11.05 0.15	–74.75 1.2	–
Przyporniak PR	950	03.08.88	–11.08	–75.5	34.8±1.7

Explanation as in Table 1

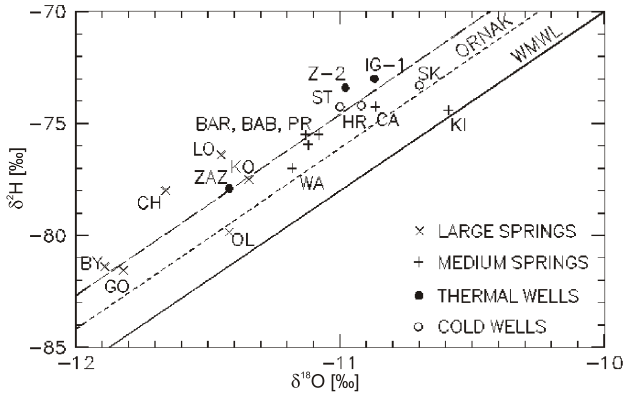

Fig. 3. Stable isotope composition of groundwaters in the Polish Tatra Mts. and their approximate line are shown in comparison with World Meteoric Water Line (WMWL) and local meteoric line (Ornak Alp)

Sample codes are given in Tables 1–4

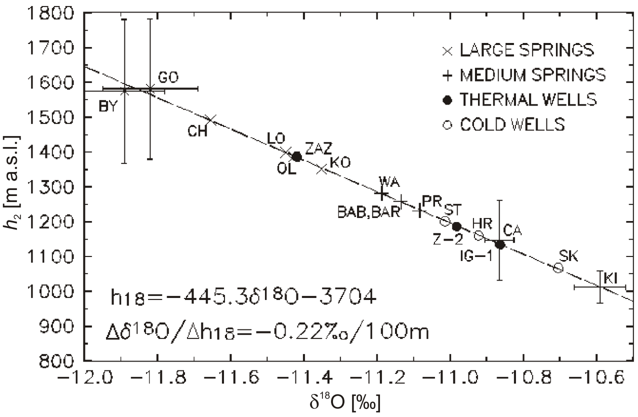

Fig. 4. Altitudes of recharge areas estimated on the basis of ^{18}O data for known extreme altitudes of Bystrej (BY) and Goryczkowe (GO) springs, and for Pod Capkami (CA) and Kiry (KI) springs

Sample codes are given in Tables 1–4

Table 3

Isotope data of deep wells, their altitudes, roofs of water bearing layers, temperatures and free water levels

Name/Code/Temperat./Distance to the Tatra	Altitude/Roof/Water level [m a.s.l.]	Date	$^{18}O_{V\text{-}SMOW}$ [‰]	$^{2}H_{V\text{-}SMOW}$ [‰]	Tritium [T.U.]
Hruby Regiel IG-2/HR/10°C/525 m	935/536/928	11.06.87	–10.98	–72.2	44.3 2.0
		27.08.87	–10.84	–74.2	41.0 1.8
		03.08.88	n.m.	n.m.	40.0 1.5
		24.06.01	–10.92	–75.1	14.8 0.9
		Median	–10.92 0.05	–74.2 1.0	–
Skocznia IG-1/SK/16.8°C/720 m	883/329/915	14.12.86	–10.70	–73.3	n.m.
		11.06.87	–10.55	–73.3	n.m.
		26.08.87	–10.85	–72.0	31.8 1.6
		Median	–10.70 0.10	–73.3 0.5	–
Zakopane IG-1/IG-1/35.5°C/1680 m	865/-675/866	08.69	n.m.	n.m.	12
		08.70	n.m.	n.m.	110
		08.71	n.m.	n.m.	190
		08.72	n.m.	n.m.	170
		08.73	n.m.	n.m.	120
		10.12.86	–10.87	–74.6	23.4 1.2
		11.06.87	–10.99	–71.9	23.9 1.2
		26.08.87	–10.79	–73.0	20.2 1.1
		03.08.88	–10.75	–72.1	20.3 1.1
		24.06.01	–10.91	–74.4	10.6 0.8
		Median	–10.87 0.05	–73.0 0.5	–
Zakopane 2/Z-2/26.4°C/1600 m	868/-196/898	10.12.86	–11.02	–71.8	59.5 3.0
		11.06.87	–11.15	–73.4	54.4 2.4
		26.08.87	–10.98	–75.2	46.2 2.1
		03.08.88	–10.83	–73.4	47.7 2.2
		24.06.01	–10.96	–73.1	19.8 1.2
		Median	–10.98 0.06	–73.4 0.5	–
Zazadnia/ZAZ/22°C/1550 m	855/-190/945	13.12.86	–11.35	–75.8	55.2 2.4
		11.06.87	–11.70	–76.0	54.2 2.4
		27.08.87	–11.49	–77.9	52.0 2.3
		03.08.88	–11.40	–78.4	49.4 2.2
		24.06.01	–11.42	–78.3	16.2 1.0
		Median	–11.42 0.07	–77.9 0.5	–

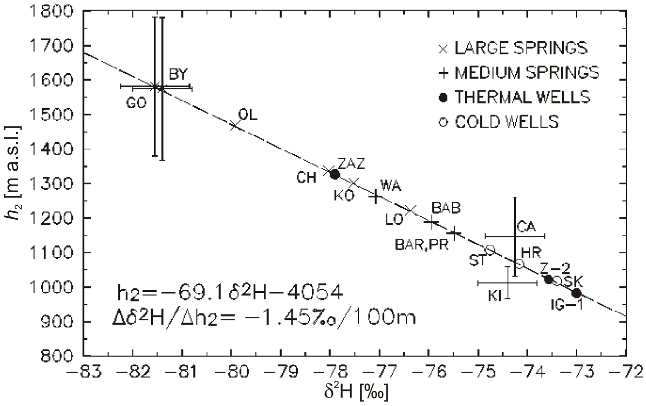

Fig. 5. Altitudes of recharge areas estimated on the basis of ^{2}H data for known extreme altitudes of Bystrej (BY) and Goryczkowe (GO) springs, and for Pod Capkami (CA) and Kiry (KI) springs

Sample codes are given in Tables 1–4

Table 4

Models fitted to tritium data and mean altitudes of recharge areas

Name/Code	Model/ — older fraction	Age [years]	P_D [–]	[–]	h_{18} [m a.s.l.]	h_2 [m a.s.l.]
Bystrej/BY	n.d.	–	–	–	1574 207^a	1574 207^a
Goryczkowe/GO	n.d.	–	–	–	1581 200^a	1581 200^a
Olczyskie/OL	n.d.	–	–	–	1381	1464
Koziarczyska/KO	EM/0	6.5	–	1.00	1350	1301
Chochołowskie/CH	DM/0 DM/0 (?)	3 5(?)	1.50 0.005	–	1491	1335
Lodowe/LO	–	n.d.	–	–	1394	1225
Kiry/KI	EPM/0	74	–	1.00	1012 46^a	1012 46^a
Pod Capkami/CA	DM/0 DM/0 (?)	11 141(?)	2.00 1.5	– –	1146 115^a	1146 115^a
Barany/BAR	EM/0	11.4	–	1.08	1252	1163
Babtystów/BAB	n.d.	–	–	–	1247	1194
Waksmundzkie/WA	n.d.	–	–	–	1274	1267
Staników Żleb/ST	n.d.	–	–	–	1217	1111
Przyporniak/PR	n.d.	–	–	–	1230	1163
Hruby Regiel/HR	DM/0	102	1.30	–	1350	1301
Skocznia IG-1/SK	n.d.	–	–	–	1061	1011
Zakopane IG-1/IG-1	DM/0.83 + EPM/0.17	8.8 100	0.007 –	– 1.27	1136	990
Zakopane 2/Z-2	DM/0	55	0.50	–	1176	997
Zazadnia IG-1/ZAZ	DM/0	50	1.00	–	1381	1329

a — independently estimated altitudes and their uncertainties (see text); (?) — model yielding doubtful results; n.d. — not determined due to insufficient number of tritium data; DM — dispersion model; EM — exponential model; EPM — exponential pisto-flow model

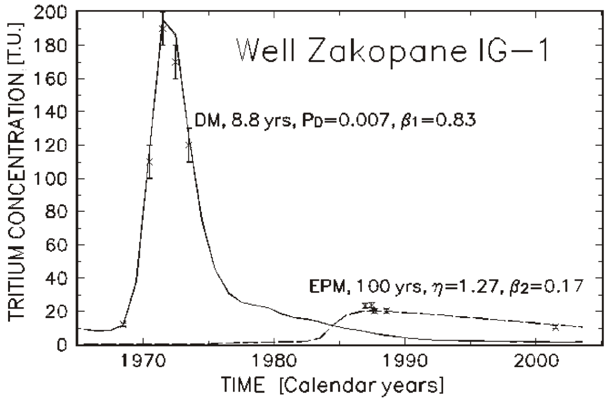

Fig. 6. Tritium data of the Zakopane IG-1 well and lumped parameter models fitted to the early and late data sets

values of parameters obtained from the interpretation procedure are given in Figure 6 and Table 4. The β_1 value obtained means that the model represents only the 17%-fraction of water ($1 - \beta_1 = 0.17$). The remaining late tritium data were corrected by subtracting tritium contents resulting from the tail part of the first model, i.e. the presence of tritium in the fast component can be ignored. To the data corrected in that way, another model was fitted under an assumption that measurable tritium is present only in the 83% fraction of water ($1 - \beta_2 = 0.83$). The results obtained indicate the presence of two distinctly different flow paths to the Zakopane IG-1 well. The fast flow path of *ca.* 9 years with little dispersion is probably related to a single karstic channel characterized by low dispersivity. That channel supplies only 17% of abstracted water with the mean age (τ_1) of *ca.* 9 years whereas the remaining part of 83% is characterized by very wide distribution of flow times with the mean age (τ_2) of 100 years. The age distributions (tracer flow times) of both flows yielded from fitted models are shown in Figure 7, and the total mean age (τ_{total}) is given by Equation [4]:

$$\tau_{total} = (1 - \beta_1) \times \tau_1 + (1 - \beta_2) \times \tau_2 = \\ = 0.17 \times 8.8 + 0.83 \times 100 = 84.5 \text{ yrs} \qquad [4]$$

The mean tritium age for the Zakopane IG-1 well considerably differs from the value of 12 years given by Małecka and Nowicki (2002). For three other wells, the tritium records are much shorter but the fitted models yield mean ages of the same order as in the case of the Zakopane IG-1 well (Fig. 8) whereas a single tritium determination for the Skocznia well is not sufficient for obtaining a quantitative age interpretation.

Quantitative interpretation of tritium data for springs is less reliable due to variable outflows though samples were rather taken during low flows when there were no flows

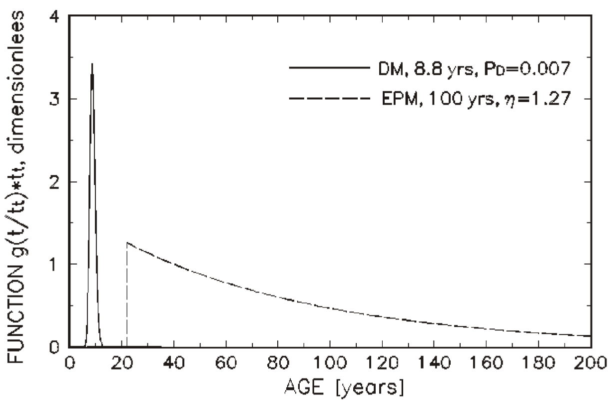

Fig. 7. Age distributions (weighting functions) of the models fitted in Figure 6 to the tritium data of the Zakopane IG-1 well

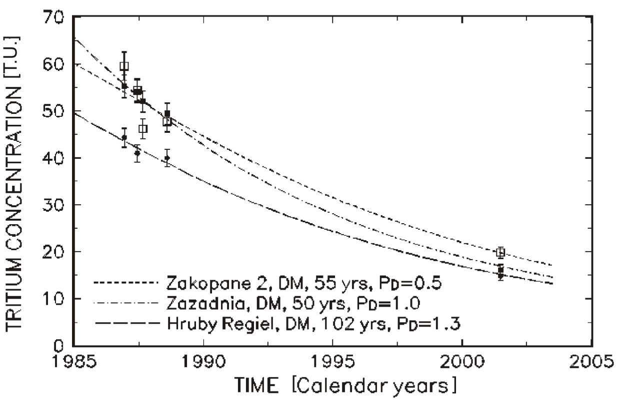

Fig. 8. Tritium data of three deep wells and their lumped-parameter models

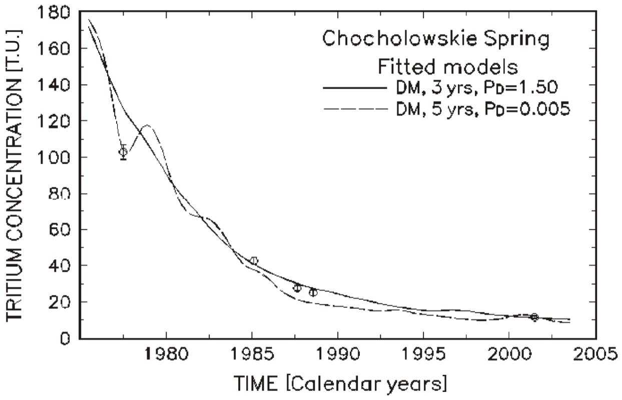

Fig. 9. Tritium data of the Chochołowskie Spring and two fitted lumped-parameter models

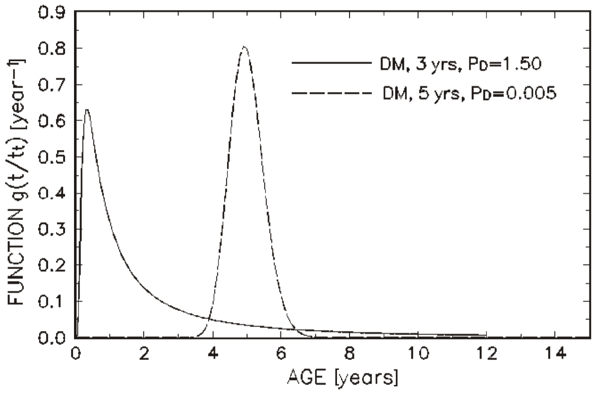

Fig. 10. Age distributions (weighting functions) of the models fitted to the Chochołowskie Spring tritium data

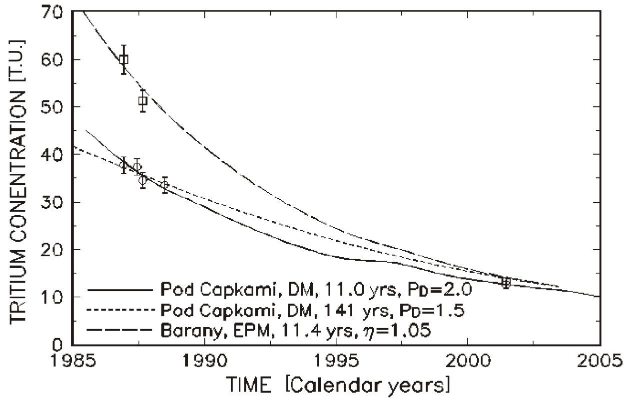

Fig. 11. Tritium data of two medium springs and three lumped-parameter models fitted to these data

through karstic channels from ponors to springs. Consequently, the following age considerations are mainly related to the flows draining the fissure and matrix porosities. In spite of the longest record available for the Chochołowskie spring, the obtained fit is far from satisfactory. Therefore, both dispersion models obtained from the fitting procedure (Fig. 9) cannot be regarded as very reliable. They yielded greatly different values of the dispersion parameter (P_D = 1.50 and 0.005), and relatively close mean ages of 3 and 5 years, respectively, though quite different age distributions shown in Figure 10. The values of the dispersion parameters are beyond the most typical range, say 0.02¸0.5, whereas the model with the mean age of 3 years and P_D = 1.5 is much more reliable due to a realistic distribution of ages characterized by prevailing low age values and a long tail resulting from slow drainage of small fissures and some micropores. The tritium data of other large springs shown in Table 1 suggest that they can probably be described by similar models.

Three examples of models fitted to the tritium data of two medium springs (Barany and Pod Capkami) are shown in Figure 11. The mean ages of these springs are evidently greater than those of large karstic springs though much lower than those of deep wells. Two different models equally well fitted to the data of the Pod Capkami spring exemplify the lack of unique solutions, which to a high degree results from the lack of systematic sampling schedules and too short records. In that particular case, the larger value of the mean age seems to be unrealistic.

HYDROGEOLOGIC PARAMETERS

Under favourable conditions, the tracer age in the saturated zone (τ_{ts}) can serve for determining some hydrogeologic parameters. For instance, if the total interconnected porosity (n), the mean flow distance (x), and the mean hydraulic gradient ($\Delta h/\Delta x$) are known or can reliably be estimated, the regional value of the hydraulic conductivity (K) can be calculated from Equation [5] (Zuber and Motyka, 1994).

$$K = n \times x/[(\Delta h/\Delta x) \times (\tau_{ts})] \qquad [5]$$

where: n — sum of the matrix (n_p), fissure (n_f), and karstic channel (n_k) porosities.

Usually n_p can replace n in Equation [5] because it significantly exceeds both n_f and n_k (Zuber and Motyka, 1998). Matrix porosity, though is easily measurable on rock samples, remains unknown for the Tatra carbonates, except for the Eocene carbonates where 5 samples yielded the mean value of 0.016 (Motyka, pers. comm.).

For tritium, the age is the sum of the tracer ages in the unsaturated and saturated zones ($\tau_t = \tau_{tu} + \tau_{ts}$). Therefore, the travel time (age) of tritium through the unsaturated zone should be subtracted from the age obtained from the lumped-parameter modelling to obtain the age in the saturated zone which is applicable in Equation [5]. When no data are available for the estimation of the age in the unsaturated zone, and the total age is put into Equation [5], the hydraulic conductivity obtained represents the lowest possible value.

For the following estimation of the hydraulic conductivities, the matrix porosity of 0.02 was assumed whereas flow distances and hydraulic gradients were estimated from the maps for the water levels and recharge altitudes given in Tables 3 and 4, respectively. For the Zakopane IG-1, the mean distance was estimated to be 3000 m and the hydraulic gradient 0.066. These values used in Equation [5] together with the mean age of 85 years yielded $K = 0.34 \times 10^{-6}$ m/s. For the Zakopane 2, Zazadnia and Hruby Regiel IG-2 wells, the following K-values were obtained: 0.90×10^{-6}, 0.63×10^{-6} and 2.5×10^{-6} m/s, respectively. The pumping tests performed in these four wells yielded: 0.23×10^{-6}, 3.2×10^{-4}, 1.5×10^{-5} and 8.3×10^{-6} m/s, respectively (Chowaniec, pers. comm.). The values of regional hydraulic conductivities obtained for particular wells from tritium ages are distinctly lower than the local values obtained from pumping tests. The geometric mean values are 0.8×10^{-6} m/s and 17×10^{-6} m/s, respectively.

For the Chochołowskie spring, the mean distance of 1500 m and the mean hydraulic gradient of 0.167 were estimated. These values used in Equation [5] with the total age of 3 years yielded $K = 1.9 \times 10^{-6}$ m/s. If the travel time through the unsaturated zone is of the same order as the travel through the saturated zone, the true hydraulic conductivity can be two times larger.

The volume of water in the groundwater system drained by spring is given as the product of the volumetric flow rate and age, whereas the volume of rock occupied by that water is given as the ratio of water volume to the total porosity. If the age of 3 years is accepted for large springs as that corresponding to the base flow of 200 to 500 L/s, the water volume of each large spring system is (19 to 48) × 10^6 m^3. This value divided by 0.02 yields the rock volume of (0.95 to 2.4) × 10^9 m^3, which seems to be definitely too large for the involved drainage areas and thickness of water bearing formations. These estimations suggest the total porosity of rocks drained by large springs to be considerably larger than 0.02.

DISCUSSION AND CONCLUSIONS

The stable isotope composition of groundwater in the Polish Tatra Mts. is distinctly differentiated due to the altitude effect. Altitudes of recharge areas of particular springs and abstraction wells obtained from the interpretation of the δ^{18}O and δ^2H values give a better insight into the flow pattern within the Zakopane aquifer and should also serve for a better interpretation of the isotope data in the whole Podhale Basin.

The tritium ages of particular sampling sites combined with the mean altitudes of recharge areas obtained from the stable isotope data served for the estimation of regional values of the hydraulic conductivity, which are characterized by low scatter. However, they are distinctly lower than those resulting from pumping tests, which suggest generally lower flow rates than those estimated from the hydraulic investigations. The discrepancy between the hydraulic conductivities found in both ways is too large to be explained by inaccurate estimation of the porosity. Most probably, the discrepancy results from the existence of obstacles to flow, which can be caused by fault planes. A large scatter of the hydraulic conductivity obtained from pumping tests results from a stronger dependence on local conditions, whereas the regional hydraulic conductivity determined from tritium ages is much less influenced by local conditions. The uncertainty of the hydraulic conductivities obtained from tritium ages can be reduced when better estimation of ages, flow distances, hydraulic gradients and porosity are obtainable.

The rock volumes of systems drained by large karstic springs estimated from the tritium ages are definitely too large, which most probably results from the inadequate estimation of the total porosity for the upper parts of the High Tatra unit drained by these springs. If the total porosity distinctly exceeds the value of 0.02 used within this work, the rock volume drained by large spring is much lower and the hydraulic conductivity of that part of the High Tatra unit is much larger than the value estimated from the tritium age, i.e. 1.9×10^{-6} m/s. Further works on tracer ages and the porosity of the investigated formation should lead to more reliable values of both parameters.

The archival records of the tritium data were satisfactorily complete only for some sampling sites to be interpreted quantitatively in terms of water ages. Unfortunately, the present tritium concentrations are not sufficiently differentiated in the investigated area to be promising for more refined age determinations by that tracer. Perhaps other transient tracers such as freons and SF_6 (IAEA, 2006) may become useful in near future for a better age identification of spring waters.

Low ^{14}C contents observed in a number of deep wells within the basin reported by Małecka and Nowicki (2002) were correctly interpreted by these authors as resulting from isotopic exchange with carbonate minerals, which is particularly effective in microporous matrix and under elevated temperatures (Małoszewski and Zuber, 1991). It seems that for the wells situated further than wells investigated within the present study, the ^{4}He dating method should yield reliable age estimations whereas the tritium ages obtained for waters close to the recharge area can probably be used to calibrate the ^{4}He excess concentrations in order to estimate ^{4}He ages. For instance, combined interpretation of ^{4}He excess concentrations and other tracers appeared to be useful for the Malm limestones in the Cracow region (Zuber *et al*., 2004) and for Triassic carbonates in the northern part of the Upper Silesia Coal Basin (Zuber *et al*., 2005) where ^{14}C dating was evidently unreliable. Judging from that experience, ^{4}He determinations combined with tritium data of young waters should also be very useful for age determinations of thermal waters in the whole Podhale Basin.

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