CATENA vol. 15, p. 289–301 Braunschweig 1988

A RECONNAISSANCE ISOTOPE STUDY OF WATERS IN THE KARST OF THE WESTERN TATRA MOUNTAINS

K. **Rozanski** & M. **Dulinski**, Krakow

Summary

Presented are results of isotope investigations of waters collected in the karstic area of the Western Tatra Mts. Altogether 35 groundwater samples have been analysed (tritium content, δD, δ^{18}O). They represent groundwaters collected on the earth surface (springs, streams, exurgences) as well as waters found in caves. Parallel, systematic isotope analyses of monthly precipitation collected at the Ornak station located in the center of the investigated area were also carried out. The results of isotope investigations fully confirm earlier suggestions that the karst system of the Western Tatra Mts consists of separate independent subsystems exhibiting weak (if any) hydraulic interconnections. Tritium data allow a semi-quantitative assessment of the mean residence time of the baseflow component in the investigated system. It is equal to at least 7÷8 years. Eventual further measurements of tritium content should allow a more precise determination of this parameter. δD and δ^{18}O analyses of the investigated waters provide a basis for assessment of the I_s/I ratio i.e. the ratio of infiltration originating from summer precipitation to the total yearly infiltration. It appears that groundwaters collected in caves exhibit on the average significantly higher D and ^{18}O content compared to groundwaters collected on the surface. Possible reasons of this effect are discussed thoroughly in the paper.

1 Introduction

Hydrology and hydrogeology of the karst in the Tatra Mts was intensively studied during the last thirty years (e.g. DABROWSKI 1962, 1967, DABROWSKI & RUDNICKI 1967, RUDNICKI 1967, GŁAZEK et al. 1979, MAŁECKA 1985, ROGALSKI 1986). It is generally accepted that karst in the Tatra Mts consists of many independent subsystems exhibiting weak (if any) hydraulic interconnections. This conclusion has been drawn from artificial tracer studies as well as from chemical and temperature data available for waters collected in this region.

Characteristic for the karst of the Tatra Mts is a latitudinal arrangement of main lithological units with a perpendicularly developed network of main valleys. This facilitates contact of shallow groundwaters with those representing deeper circulation pathways.

ISSN 0341–8162

D–3302 Cremlingen-Destedt, W. Germany
0341–8162/88/5011851/US$ 2.00 + 0.25

Up to now, the dynamics of groundwater flow in the karst of the Tatra Mts was studied using artificial tracers, mainly dyes. However, these studies were of pure qualitative character providing information mainly on hydraulic interconnections within the system (DABROWSKI 1967, DABROWSKI & GŁAZEK 1968, GŁAZEK et al. 1979, ROGALSKI 1984). Recently, an attempt was undertaken to interpret artificial tracer data more quantitatively by means of mathematical models of tracer transport in groundwater systems (ROGALSKI 1986). It was found from dye experiments in the Kościeliska and Chochołowska valleys that the mean residence time of groundwater in the investigated flowpaths was in the order of some tens to a few hundreds of hours. It was also possible to assess mean velocities of groundwater between the injection and the sampling points as well as volumes of the aquifer adjacent to groundwater circulation pathways.

In view of the above mentioned studies it was interesting to apply also environmental tracers (tritium, deuterium, oxygen-18) in order to gain more detailed information on dynamics and structure of groundwater flow in the karst of the Tatra Mts. It is worth to note here that environmental tracers enter the groundwater system in the course of the natural infiltration process. Consequently, they are much better suited for investigations of the structure and basic parameters of the whole groundwater system, then artificial tracers providing information only about the spiked part of the system.

Tritium is a β-emitting radioactive isotope of hydrogen with a half-live of 12.43 years. As a result of nuclear weapon tests it is present in considerable amounts in atmospheric precipitation since the early fifties. Temporal variations of tritium content in precipitation are pretty well known both on global and regional scales. Variations of tritium content in precipitation provide a basis for the construction of the so-called tritium input function to hydrogeological systems (e.g. GRABCZAK et al. 1984). Concentration of tritium in water is expressed usually in tritium units (T.U.). One Tritium Unit represents the concentration of tritium equal 1 atom of tritium per 10^{18} atoms of hydrogen.

Stable isotopes of water, deuterium and oxygen-18, are also widely applied as natural tracers in hydrogeological studies. Their concentration in precipitation over mid latitudes exhibits characteristic seasonal fluctuations with maximum during summer and minimum during winter months. Concentration of D and ^{18}O is expressed usually in δ-values defined as a permille deviation from internationally accepted standard SMOW (Standard Mean Ocean Water). All isotope analyses presented in this paper have been performed in the Department of Environmental Physics (Institute of Physics and Nuclear Techniques, Academy of Mining and Metallurgy, Krakow, Poland).

The isotope investigations presented in this paper belong to a complex isotopic study of carbonate cave deposits of central and southern Poland carried out for palaeoclimatic purposes (ROZANSKI & DULINSKI 1985, ROZANSKI & DULINSKI 1987). The study area is shown in fig.1. Sampling comprised monthly precipitation, surface outflows (streams, springs and exurgences) as well as vadose seepage waters in caves. Results of isotope analyses of these waters are thoroughly discussed below.

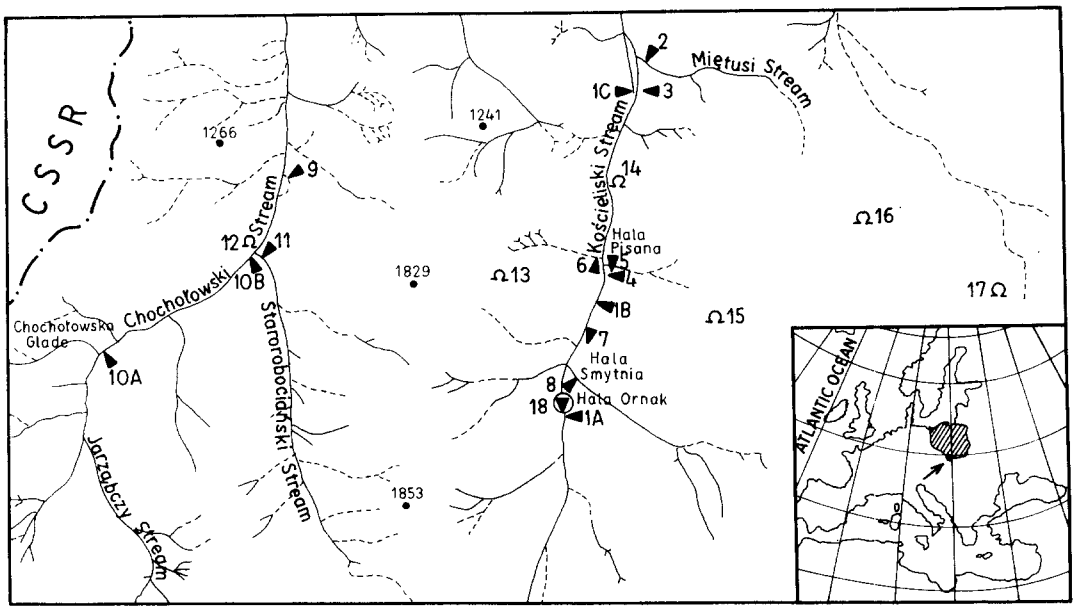

Fig. 1: *The investigated part of the karstic system in the Western Tatra Mts. Sampling sites are indicated by numbers.*
1 - Kościelski Stream (A - Ornaczańska Glade, B - small bridge near Hala Ornak, C - Kraszewski Gate), 2 - Mietusi Stream, 3 - Lodowe Spring, 4 - Pisana resurgence, 5 - Pisana exurgence, 6 - spring on the Pisana Glade, 7 - spring near the Pol Cross, 8 - Tomanowy Stream, 9 - Chochołowskie exurgence, 10 - Chochołowski Stream (A - near Jarzabcza Glade, B - before Starorobociański Stream), 11 - Starorobociański Stream, 12 - Szczelina Chochołowska Cave, 13 - Bańdzioch Kominiarski Cave, 16 - Mietusia Cave, 17 - Wielka Snieżna Cave, 18 - meteorological station at the Hala Ornak.

2 Results of Measurements

Precipitation and groundwater samples have been collected in the study area starting from October 1983 till January 1986. A special meteorological station was installed in the center of the investigated karstic region at the Hala Ornak (Kościelska Valley) in order to collect the monthly precipitation for isotope analyses. The amount of precipitation as well as surface air temperature was also recorded there. Another precipitation station was working at the same time at Krakow, which is situated ca. 100 km to the north, at an elevation about 900 m lower than the Ornak station. Monthly precipitation data for both stations are summarized in fig.2. Temporal variations of tritium content in the investigated groundwaters and precipitation are shown in fig.3. Analogous comparison for deuterium content is given in fig.4. The relationship between D and ^{18}O content of the analysed precipitation and groundwater samples is shown in fig.5. Position of the World Meteoric Water Line having an equation $\delta D = 8 \times \delta^{18}O + 10$ as well as the best fit line representing precipitation data from Krakow are also indicated on this figure. Inserted are also frequency distribution histograms of the deuterium content in surface outflows and vadose seepage waters in the study area.

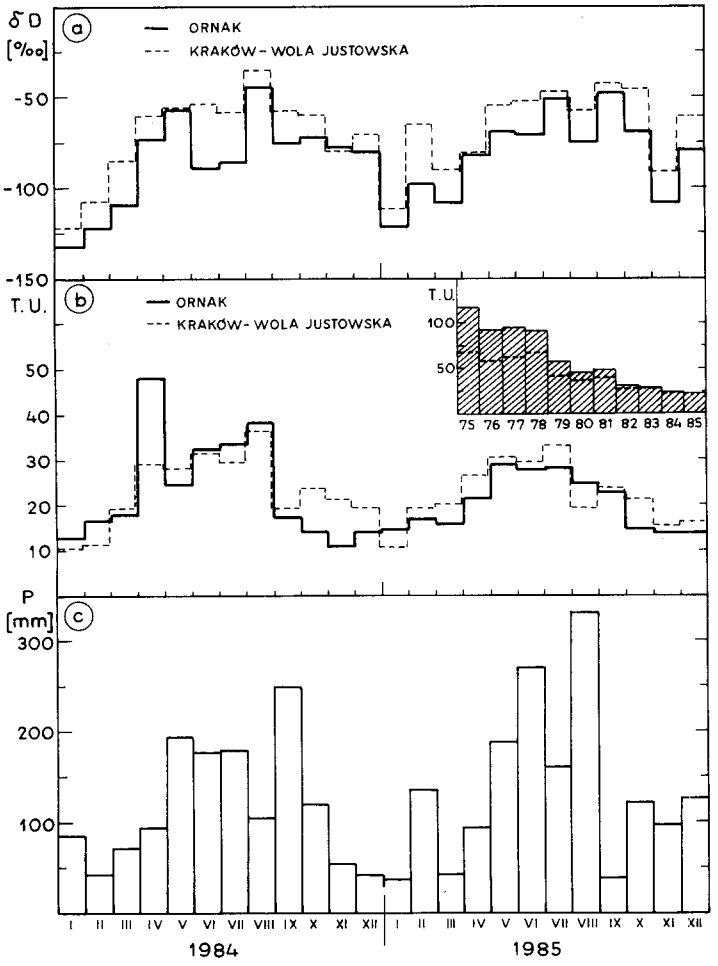

Fig. 2: *a - Changes in deuterium content of monthly precipitation collected at the Krakow and Ornak stations during the period January 1984 – December 1985.*

b - Changes in tritium content of monthly precipitation collected at the stations above. Inserted histogram shows calculated tritium input function for the Western Tatra Mts (see text for details). Dashed lines in the histogram represent tritium concentrations corrected for decay on 1st of January 1985.

c - Variations in amount of monthly precipitation as observed at the Ornak station during the sampling campaign (1984–85).

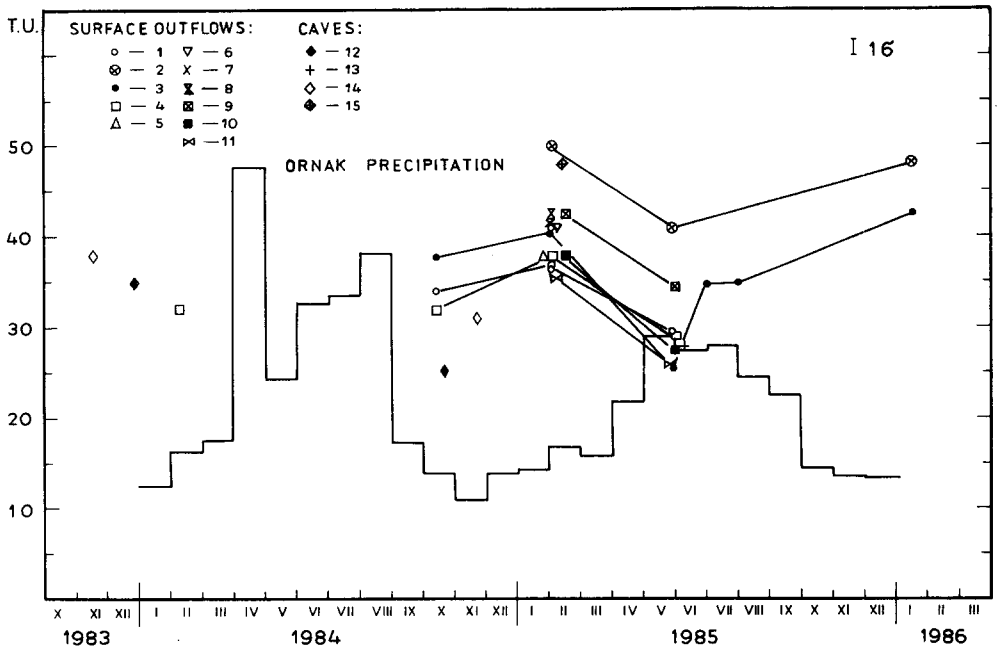

Fig. 3: *Time series of tritium content in the investigated waters. Histogram shows seasonal fluctuations of tritium content in precipitation collected in the study area. Description of the sampling sites as in fig.1.*

3 Discussion

3.1 Isotopic Composition of the Monthly Precipitation

As can be seen from fig.2b, a good correlation is observed for tritium content in precipitation collected at the Ornak and Krakow stations (correlation coefficient 0.85). One notable exception is the precipitation collected during April 1984 exhibiting 47.7 TU in Ornak, whereas in Krakow only 29 TU were observed. This relatively high value recorded at Ornak significantly exceeds seasonal fluctuations (cf. fig.2b). During that particular month other European precipitation stations did not record any elevated tritium contents. This fact suggests purely local character of the observed event. It may result from accidental emission of tritium from one of the czechoslovakian nuclear power stations located on the southern side of the Tatra Mts. Such increased tritium concentrations in precipitation caused by near-ground releases of tritium from nuclear facilities have already been observed over Europe (WEISS et al. 1979, SCHOCH-FISCHER et al. 1983). Nevertheless, accidental contamination of this particular sample during sampling and/or transportation cannot be excluded either. The correlation coefficient quoted above was calculated without the April 1984 data.

A very good correlation between the Krakow and Ornak precipitation data is also observed for D and ^{18}O content. However, a systematic shift to-

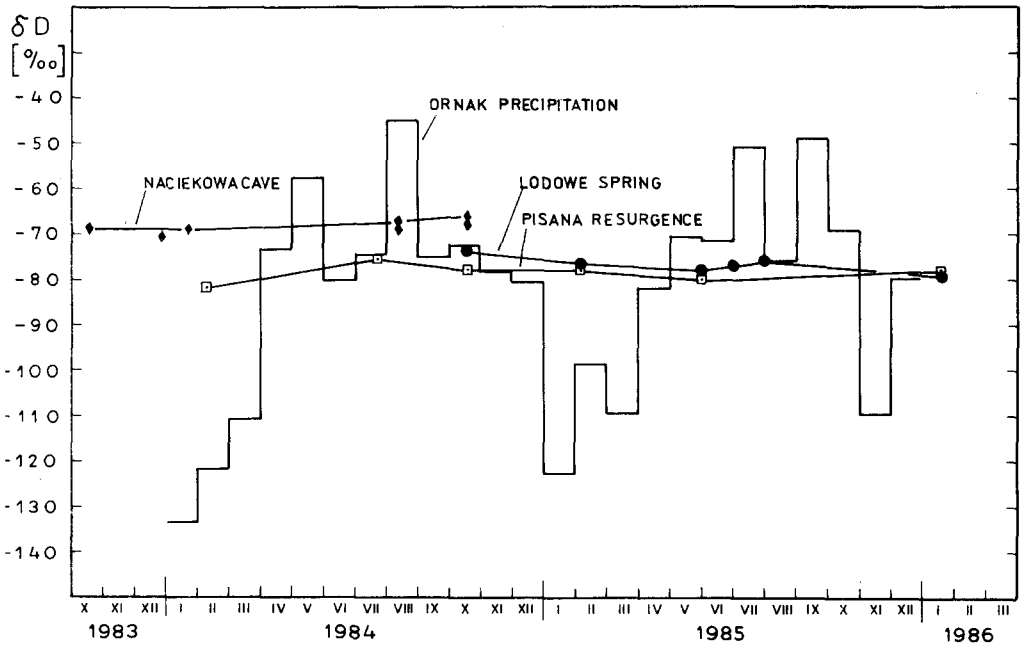

Fig. 4: *Time series of deuterium content of the selected waters in the study area. For comparison, deuterium content in monthly precipitation is also indicated.*

wards more negative values of δD and δ^{18}O occurs for the Ornak precipitation when compared to the Krakow station (cf. tab.1 and fig.5). The observed shift is mainly due to the so-called altitude effect, which is a clear-cut tendency to more and more isotopically depleted precipitation with increasing elevation of the sampling site. The difference in elevation between Krakow and Ornak stations results in the isotope gradient of δD and δ^{18}O equal to $1.4^0/_{00}$/ 100 m and $0.24^0/_{00}$/100 m, respectively. Although these values are slightly lower than reported in the literature (1.5 to $4^0/_{00}$/100 m for δD and 0.15 to $0.5^0/_{00}$/100 m for δ^{18}O — YURTSEVER & GAT 1981), one should take into account the fact that in our specific case the true altitude effect is partly compensated by the so-called latitude effect, i.e. the tendency to have more depleted precipitation in both D and ^{18}O when moving from the tropics towards the poles.

As can be seen in fig.5, monthly precipitation collected at the Ornak station reveals a mean deuterium excess value of ca. $7^0/_{00}$ higher than the precipitation collected at the Krakow station. The deuterium excess is commonly defined as a difference: $d = \delta D - 8 \times \delta^{18}O$. Two effects have to be considered if one attempts to explain the observed shift of local meteoric line towards higher d-excess values, when moving from a lowland area to the mountains. First, atmospheric water vapour may have a different isotopic composition when arriving from different oceanic source re-

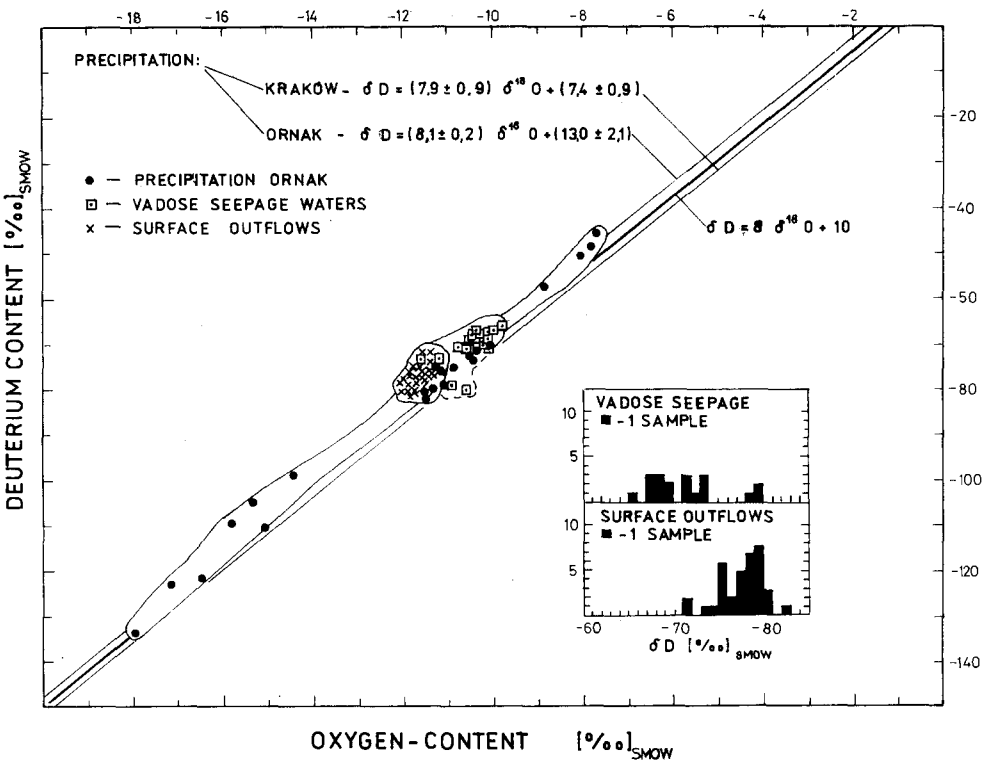

Fig. 5: *δD - δ^{18}O relationship for precipitation and groundwater samples collected in the karstic area of the Western Tatra Mts. The straight lines represent best fit of the monthly precipitation data.*

	Number of analyses	δD (‰)	δ^{18}O (‰)	d-excess (‰)
1. Precipitation*				
- Ornak Station 1984–85 (1100 m a.s.l.)	24	-77.6 ± 5.6	-11.26 ± 0.71	12.5 ± 2.1
- Krakow Station 1984–85 (205 m a.s.l)	24	-64.9 ± 5.9	- 9.12 ± 0.77	5.4 ± 1.7
2. Surface outflows (springs, streams, exurgences, resurgences)	43	-77.6 ± 0.4	-11.59 ± 0.04	15.1 ± 0.5
3. Vadose seepage waters	19	-71.3 ± 0.9	-10.64 ± 0.13	13.6 ± 1.4

* Weighted mean δD values are indicated (weighing by amount of monthly precipitation.)

Tab. 1: *Average deuterium and ^{18}O content of monthly precipitation, surface outflows and vadose seepage waters collected in the karstic area of the Western Tatra Mts during the period October 1983 – January 1986.*

gions. This is unlikely in our case due to the relatively small distance between the two considered stations. Also because of the fact that westerly circulation prevails over Europe, which brings water vapour from subtropical regions of the Atlantic Ocean with well defined isotopic characteristics. Second, a more probable effect is connected with the partial evaporation of raindrops on their way down from the cloud to the earth surface. An average distance between the mean cloud base and the earth surface is substantially smaller in the mountains when compared to lowland regions. Consequently, a smaller portion of raindrops is expected to evaporate in an unsaturated atmosphere below the cloud base level. Since deuterium excess of evaporating water decreases when the process proceeds on, the observed difference in position of the local meteoric line of the δD - $\delta^{18}O$ diagram becomes understandable. Detailed considerations of this effect show that under typical climatic conditions prevailing over mid-latitudes the postulated change of the d-excess value of falling raindrops is quite plausible (ROZANSKI 1987). It is worth to mention here that a clear-cut tendency to observe higher d-excess values with increasing elevation of the sampling point for shallow groundwaters (mainly springs and wells) was recently observed also in the Sudety Mts (W. CIEZKOWSKI, unpublished results). This fact confirms to some extend the explanation discussed above for the high deuterium excess values observed in precipitation and groundwater samples from the Western Tatra Mts.

3.2 Isotopic Composition of Surface Outflows and Seepage Waters

Fig.3 shows temporal variations of tritium content in the investigated groundwaters, superimposed on the seasonal fluctuations of tritium in monthly precipitation. Despite of considerable spread of the data points, a distinct trend is visible for most of the analysed waters: they exhibit relatively high tritium concentrations during winter months and correspondingly low values during late spring and summer, which is an inverse effect to that observed in precipitation. Such a situation is probably caused by the fact that during winter months the baseflow component dominates (see e.g. GIEYSZTOR 1961). The apparent decrease of tritium content during summer is due to admixture of freshwater originating from melting of the snow cover and/or precipitation infiltrating during the preceding months. The freshwater component is significantly depleted in tritium when compared to the baseflow component. Assuming that the samples collected on 31th of May, 1985 represent a two-component mixture and that the average tritium content of the baseflow component is equal to ca. 40 TU, one can calculate the proportion of the freshwater component in the sampled waters. It is equal to about 85%. A weighted average of tritium content in monthly precipitation collected at the Ornak station between March and May 1985 was assumed as representative value for the second end-member of the postulated mixing. The choice of these particular months resulted from an analogous estimate carried out using deuterium data. Only the period chosen above provides comparable results for tritium and deuterium data.

Remarkable is a distinctly higher tritium content in the Mietusi stream when compared to the Kościeliski stream as well as to other waters sampled in the Kościeliska valley. This difference in connection with relatively high tritium content in seepage water from Mietusia cave suggests absence of direct hydraulic interconnection between the catchment areas of these two streams despite of their close location.

The tritium data presented above undoubtedly indicate a variable impact of the baseflow component to groundwater flow in the investigated karstic system. Mathematical models describing transport of environmental traces in groundwater systems (MAŁOSZEWSKI & ZUBER 1982, ZUBER 1986) cannot be directly applied for quantitative interpretation of these data mainly due to the short period of observation. Nevertheless, even this limited data record allows already a semi-quantitative estimate of the mean residence time of water in the investigated karstic system. This estimate was based on comparison of the measured tritium concentrations in groundwaters with those expected from the analysis of the tritium input function evaluated for the considered region.

The tritium input function for the given hydrogeological system is defined by the following equation (e.g. GRABCZAK et al. 1984):

$$C_k = [\alpha\Sigma(P_{ki}C_{ki})_s + \Sigma(P_{ki}C_{ki})_w]/[\alpha\Sigma(P_{ki})_s + \Sigma(P_{ki})_w] \quad (1)$$

where

C_k = tritium content of water infiltrating in the given year. Row of C_k values forms the tritium input function.

C_{ki} = tritium content in precipitation representing the given month,

P_{ki} = the amount of precipitation representing the given month,

α = the ratio of summer to winter infiltration coefficients.

Subscripts s and w stay for summer and winter months, rspectively, and subscript i stays for January, February, March, October, November, December in the case of winter months and for April to September in the case of summer months.

The tritium input function representing the investigated karstic region was evaluated for the time period 1975–1985. The procedure was as follows:

a) the monthly tritium data for the Ornak station for the time period 1975–1983 have been derived from precipitation data available for the Krakow station using the correlation equation found for the 1983–1985 period,

b) the amount of monthly precipitation at the Ornak station for the time period 1975–1983 was assumed to be identical with that of the station Kasprowy Wierch, situated ca. 9 km to the SE and having nearly the same yearly sum of precipitation (Ornak 1984–1985 — 1540 mm, Kasprowy Wierch 1931–1960 — 1610 mm) as well as similar seasonal distribution (MALECKA 1985a, INSTYTUT METEOROLOGII I GOSPODARKI WODNEJ 1973)

c) the ratio of the infiltration coefficients has been evaluated with the aid of stable isotopes (see dicussion below).

The estimated tritium input function is shown in fig.2b in form of the inserted histogram. Comparison of this histogram with the observed tritium concentrations in the sampled groundwaters reveals that the mean residence time of the baseflow component is in the order of

7–8 years. However, its upper limit can be much higher. The main reservoirs of tritium in the investigated karstic system are represented by the soil cover as well as by portions of carbonate rocks (limestone) adjacent to fractures and fissures through which the flow is realized. The above estimate of the mean residence time of the baseflow component is confirmed to some extent by the stable isotope data. As can be seen in fig.4, distinct seasonal fluctuations of deuterium content observed in precipitation are practically absent in the vadose seepage as well as in the surface outflows. Such situation is expected when the mean residence time of water in the investigated groundwater system is larger than ca. 2 years (MAŁOSZEWSKI et al. 1983).

Comparison of the heavy-isotope content of surface outflows and seepage waters shows that the latter are shifted on the local meteoric water line towards higher δD and $\delta^{18}O$ values (cf. fig.5 and tab.1) whereas the average isotopic composition of surface outflows remains identical with the yearly weighted mean of precipitation in the investigated area. A reconnaissance character of the study done so far does not allow any definite explanation of this interesting phenomenon. Two different hypotheses can be formulated:

1. For unknown reasons the seepage waters in the investigated caves are biased towards summer precipitation when compared to surface outflows. One may speculate that surface outflows contain, on the average, larger proportions of water originating from winter precipitation (especially during periods of snow melting in the area) characterized by low deuterium and ^{18}O content. On the other hand, absence of seasonal fluctuations in isotopic composition of these waters (fig.4) seems to reject such a possibility.
2. The heavy isotope content of seepage waters is modified in situ by evaporation and/or isotope exchange processes. Evaporation is unlikely due to high relative humidity in caves where water samples have been collected. A typical value measured by us was $98\pm2\%$. Moreover, the observed isotope shift along the local meteoric line also seems to reject this process. The isotope exchange at specific conditions prevailing in the investigated caves (atmosphere saturated with respect to water vapour, very low discharge rates of the waters sampled) may serve as effective mechanism modifying isotopic composition of seepage waters. It should be noted that this process will change the heavy-isotope content of seepage water along the local meteoric line, which is our case. However, the ultimate condition for producing the observed isotopic enrichment of seepage waters is substantial isotope disequilibrium between these waters and the water vapour present in the cave atmosphere. The vapour should be enriched compared to its equilibrium isotopic composition at the actual temperature of the cave. Such situation is likely to occur during summer months when downward transport of isotopically heavy atmospheric moisture is facilitated by the existing gradient of water vapour content between the surface and the cave atmosphere.

Clearly, more comprehensive investigations are necessary to find out which of these two alternatives is realized in nature. It is still to be shown whether the discussed effect has purely local charac-

ter or occurs also in other karstic regions. Moreover, its temporal behaviour has to be studied as well.

If one accepts the first hypothesis suggesting the existence of seasonal bias towards summer precipitation in seepage waters, it is possible to estimate the ratio of infiltration originating from summer precipitation to total yearly infiltration for both groups of the analysed groundwaters. This ratio can be expressed by the following equation:

$$I_s/I = (\delta P_w - \delta G)/(\delta P_w - \delta P_s) \quad (2)$$

where

I_s, I = mean infiltration originating from summer precipitation and mean yearly infiltration, respectively,

δP_w = average isotopic composition ($\delta D, \delta^{18}O$) of summer precipitation weighted by amount of precipitation,

δG = average isotopic composition ($\delta D, \delta^{18}O$) of the investigated groundwaters.

Between the I_s/I ratio and the α coefficient (cf. eq.1) the following relationship occurs (GRABCZAK et al. 1984):

$$(I_s/I)^{-1} = 1 + \Sigma(P_i)_w/(\alpha\Sigma(P_i)_s) \quad (3)$$

The calculated I_s/I ratios for the analysed surface outflows and seepage waters are summarized in tab.2. Although eqs.(2) and (3) are basically valid for groundwaters, they can be also applied for waters containing some proportion of surface runoff. The necessary condition is that this runoff represents the average composition of infiltrating water, i.e. the evaporation can be neglected. This condition is fulfilled in our specific case. As it appears from tab.2, seepage waters indeed exhibit a significantly higher I_s/I ratio than the surface outflows. The average α coefficient applied in calculations of the tritium input function (eq.1) has been estimated using the average I_s/I ratio found for the investigated region, which is equal 0.76 (tab.2.)

However, one should be very careful when considering the estimated I_s/I ratios. As can be seen in fig.5, the frequency distribution histogram for deuterium content of seepage waters suggests the existence of few separate groups of samples having different isotopic composition. This type of frequency distribution of the isotope data may be caused by the influence of the altitude effect, which was neglected in the above calculations. Correction of this effect is difficult due to the fact that the elevations at which the analysed waters have infiltrated cannot be determined precisely. Consequently, the numbers quoted in tab.2 for the I_s/I ratios should be considered as a rough estimate representing the whole investigated area, while the true values for particular parts of this area may differ significantly.

4 Concluding Remarks

The application of environmental tracers to hydrogeological investigations of karstic systems in the Western Tatra Mts allows some important conclusions about the dynamics and stucture of groundwater flow in this region. Results of isotope investigations presented above confirm earlier suggestions that the karst in the Western Tatra Mts consists of many independent subsystems with weak hydraulic interconnections.

Tritium measurements of precipitation and groundwaters in the area made possible a semi-quantitative estimate of the mean residence time for the baseflow

Types of waters sampled	$\frac{\delta P_s(D)}{\delta P_s(^{18}O)}$	$\frac{\delta P_w(D)}{\delta P_w(^{18}O)}$	$\frac{\delta G(D)}{\delta G(^{18}O)}$	$\frac{I_s/I(D)}{I_s/I(^{18}O)}$
1. Monthly precipitation	$\frac{-69.5\pm3.8}{-10.22\pm0.43}$	$\frac{-94.9\pm6.5}{-13.45\pm0.81}$		
2. Surface outflows (springs, streams exurgences, resurgences)			$\frac{-77.6\pm0.4}{-11.59\pm0.04}$	$\frac{0.68\pm0.13}{0.58\pm0.17}$
3. Vadose seepage waters			$\frac{-71.3\pm0.9}{-10.61\pm0.13}$	$\frac{0.94\pm0.14}{0.87\pm0.18}$ *

* calculated under assumption that seasonal bias exists towards summer precipitation in formation of vadose seepage in the study area, when compared to the surface outflows (see text for details)

Tab. 2: *Mean seasonal δD and $\delta^{18}O$ values for waters collected in the karstic region of the Western Tatra Mts. The ratio I_s/I represents the mean share of infiltration originating from summer precipitation to the total yearly infiltration.*

component representing the whole investigated karstic system. This time is at least 7–8 years, while its upper limit can be much higher.

Stable isotopes in the investigated groundwaters and precipitation allow an assessment of the ratio of infiltration originating from summer precipitation to the total yearly infiltration in the investigated area. The stable isotope data suggest that seepage waters in the study area are biased towards summer precipitation when compared to surface outflows (springs, streams, exurgences).

Further, more detailed isotope studies of the karst in the Tatra Mts would be of great value. Especially, the continuation of tritium measurements is essential for eventual future use of mathematical models for quantitative interpretation of isotope data collected in this region.

Acknowledgement

Thanks are due to the authorities of the Tatra National Park for the permission to collect water samples in the Tatra Mts. Members of the Student's Caving Club (Academy of Mining & Metallurgy, Krakow) helped considerably in collecting seepage waters from caves. The authors are grateful to A. Zuber for critical comments on an early version of the manuscript.

References

DABROWSKI, T. (1962): Karstic waters in Kościeliski Stream. (in Polish). Speleologia, **2**, No. 2–4, 21–25.

DABROWSKI, T. (1967): Underground flows of karstic streams in the Western Tatra Mts. (in Polish). Acta Geologica Polonica, **17**, 593–622.

DABROWSKI, T. & RUDNICKI, J. (1967): Dye tracer experiments in karstic waters of the Czerwone Wierchy massif. (in Polish) Speleologia, **3**, No. 1, 31–34.

DABROWSKI, T. & GŁAZEK, J. (1968): Investigation of karstic flows in the eastern part

of the Tatra Mts. (in Polish). Speleologia, **3**, No. 2–4, 85–98.

GIEYSZTOR, I. (1961): Hydrological studies of streams in the Tatra Mts. (in Polish). Prace Geograficzne, No. **26**, 1–80.

GŁAZEK, J., GRODZICKI, J., RUDNICKI, J. & WOJCIK, Z. (1979): Karst in the Tatra Mts. (in Polish). Przeglad Geologiczny, **7**, 377–380.

GRABCZAK, J., MAŁOSZEWSKI, P., ROZANSKI, K. & ZUBER, A. (1984): Estimation of the tritium input function with the aid of stable isotopes. CATENA **11**, No. 2–3, 105–114.

INSTYTUT METEOROLOGII I GOSPODARKI WODNEJ (1967): Climatological Atlas of Poland — Tables, Vol. **3**, 22.

MAŁECKA, D. (1985): Importance of stationary investigations in studies of hydrological regime of karstic springs and exurgences in the Tatra Mts. (in Polish). Aktualne Problemy Hydrogeologii, AGH Publ. Office, Krakow, 119–131.

MAŁECKA, D. (1985a): Hydrogeological studies of the karst in the Tatra Mts. (in Polish). Gacek, No. **2**, 14–30.

MAŁOSZEWSKI, P., RAUERT, W., STICHLER, W. & HERMANN, A. (1983): Application of flow models in an alpine catchment area using tritium and deuterium data. Journal of Hydrology, **66**, 319–330.

MAŁOSZEWSKI, P. & ZUBER, A. (1982): Determining the turnover time of groundwater systems with the aid of environmental tracers. I. Models and their applicability. Journal of Hydrology, **57**, 207–231.

ROGALSKI, R. (1984): Tracer studies of groundwater flow in the Chochołowska Valley, Western Tatra Mts. (in Polish). Przeglad Geologiczny, No. **4**, 223–226.

ROGALSKI, R. (1986): Quantitative interpretation of trace experiments performed in the karst of the Western Tatra Mts, Poland. Proc. 5th Int. Symp. on Underground Water Tracing, Athens, 22–27 Sept. 1986 (in press).

ROZANSKI, K. & DULINSKI, M. (1985): Deuterium and oxygen-18 content of fluid inclusions trapped in carbonate cave deposits. Proc. Int. Kolloquium, 7–13 Sept., Freiberg (in press).

ROZANSKI, K. & DULINSKI, M. (1987): Deuterium content of European palaeoinfiltration waters as inferred from isotopic composition of fluid inclusions trapped in carbonate cave deposits. Proc. Int. Symp. on the Use of Isotope Techniques in Water Resources Development, 30 March – 3 April, IAEA, Vienna.

ROZANSKI, K. (1987): Stable isotopes of water in atmospheric part of the hydrological cycle. (in Polish). Zeszyty Naukowe AGH, Seria Fizyka, No. **10**, Krakow, 1–101.

RUDNICKI, J. (1967): Origin and age of the Western Tatra caverns. (in Polish). Acta Geologica Polonica, **17**, 521–593.

SCHOCH-FISCHER, H., ROZANSKI, K., JACOB, H., SONNTAG, C., JOUZEL, J., OSTLUND, G. & GEYH, M.A. (1984): Hydrometeorological factors controlling the time variations of D, ^{18}O and ^{3}H in atmospheric water vapour and precipitation in the northern westwind belt. In: Isotope Hydrology 1983, IAEA, Vienna, 3–31.

WEISS, W., BULLACHER, J. & ROETHER, W. (1979): Evidence of pulsed discharges of tritium from nuclear energy installations in central European precipitation. In: Behaviour of Tritium in the Environment, IAEA, vienna, 17–31.

YURTSEVER, Y. & GAT, J.R. (1981): Atmospheric waters. In: Stable Isotope Hydrology. Deuterium and Oxygen-18 in the Water Cycle. Technical Report Series No. **210**, IAEA, Vienna, 103–139.

ZUBER, A. (1986): Mathematical models for interpretation of environmental radioisotopes in groundwater systems. In: Handbook of Environmental Isotope Geochemistry, Vol. **2**. The Terrestrial Environment B., Elsevier Sci. Publ. Comp., Amsterdam-Oxford-New York, 1–55.

Address of author:
K. Rozanski, M. Dulinski
Institute of Physics and Nuclear Techniques
Academy of Mining and Metallurgy
al. Mickiewicza 30
30-059 Krakow, Poland