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Selected hydrogeological parameters calculated for Tatric vaucluse springs

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The analysis of the drying up curves is essential for the recognition of hydroregime in the Tatra karst areas. The most of big springs and karst springs are characterized by the drying up curves having two parts with the completely different slope of the curve. The steep section represents, according to this interpretation, a local groundwater basin, and the section with mild slope represents a regional water basin. For the karst springs selected the calculations of the average underground outflow have been made using various methods. The basic outflow, average "drying up" coefficient and Q_{RO} from Mangin formula have been estimated as well.

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INTRODUCTION

Stationary investigations of vaucluse springs have a immense role in hydrogeological investigations of karst areas. Vaucluse springs represent the karst waters regime most completely. Systematic, contemporaneous observations of stationary investigations allow to determine the reaction of springs to climatic features annually as well as multi-annually (D. Małecka, 1993). Particularly important are stationary investigations of vaucluse springs in mountainous areas, as it is practically impossible there to separate the influence of fissure or pore waters from the influence of fissure-karst waters. Investigations of groundwater runoff from Tatra karst areas were based on the results from stationary observations mainly in the most important Tatra vaucluse springs (Fig. 1). For many years they all have been undergoing stationary observations by a group of scientists from the Institute of Hydrogeology and Engineering Geology of the Warsaw University under the leadership of D. Małecka (D. Małecka, 1984). Water-marks have been installed on all vaucluse springs, two have been supplied with limnigraphs (on Lodowe vaucluse spring since 1989, on Chochołowskie vaucluse spring since 1992) which automatically register fluctuations of groundwater level. The results of stationary observations (D. Małecka, 1993, 1997; D. Małecka, W. Humnicki, 1989; D. Małecka *et al.*, 1985; G. Barczyk, 1997, 1998) were the base for calculations for all vaucluse springs.

HISTORICAL OVERVIEW

The interest for large karst springs from Tatra Mts. can be dated back to the middle of the XIX century. Between 1829 and 1860 L. Zejszner supervised systematic hydrographic observations of the Tatra Mts. (J. Głazek, 1995), which were compiled in two of his theses (L. Zejszner, 1844, 1852). The first scientific informations about such karst springs as the Chochołowskie, Lodowe and Bystre appeared under his influence. L. Zejszner (1852) also introduced the term "vaucluse spring" into specialist literature (J. Szaflarski, 1972). The rapid development of investigations on the Tatra karst between the two world wars was concentrated mainly on exploration problems. Separate hydrogeologic investigations connected with vaucluse springs were not carried out, nevertheless worth noting is the first monograph of karst phenomena of the Polish Tatra Mts. by A. Wrzosek (1933).

After the World War Two the hydrogeologic investigations of the Tatra karst were begun by followers of J. Gołąb (H. Sobol, 1959; T. Dąbrowski, 1967; T. Dąbrowski, J. Rud-

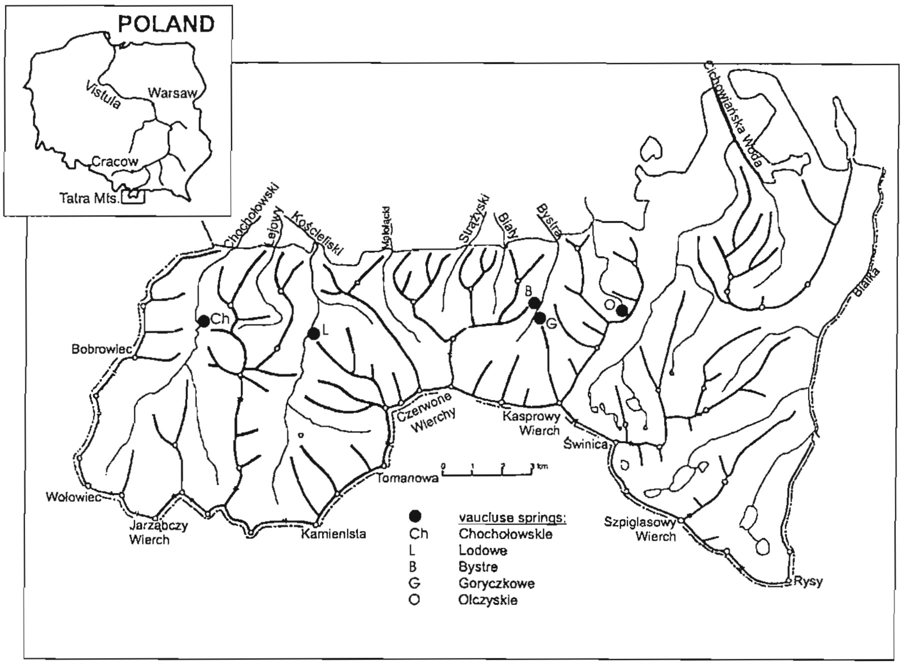

Fig. 1. Location of the karst (vaucluse) springs in Tatra Mts.

nicki, 1967; T. Dąbrowski, J. Głazek, 1968; T. Solicki, B. Koisar, 1973). These investigations, particularly stressing the role of vaucluse springs in creating the hydrogeologic regime of the area, were later continued by the group of D. Małecka (D. Małecka, 1985*a*, *b*, 1993, 1997; D. Małecka, W. Humnicki, 1989; J. Pachla, W. Zaczkiewicz, 1981; G. Barczyk, 1993, 1994, 1997, 1998).

TATRA VAUCLUSE SPRINGS

The stationary observations carried out from the mid-seventies in the Tatra Mts. by the group of D. Małecka include among others six main vaucluse springs: Chochołowskie, Lodowe, Bystre (Upper and Lower), Goryczkowe and Olczyskie (Fig. 1, Tab. 1) (D. Małecka, 1993, 1997).

Table 1

Characteristics of main Tatra vaucluse springs

Vaucluse spring	Stream	Altitude [m a.s.l.]	Outflow type	Geology	Recharge area/karst flows
Chochołowskie	Chochołowski	above 988	(+20% recharge from stream)	outflow from limestones and dolomites of the lower Sub-Tatric Succession	recharge from Chochołowski Stream drainage basin (*ca.* 7 km^2); documented karst connections with Szczelina Chochołowska and Rybia caves
Lodowe	Kościeliski	above 974	ascent	outflow in contact zone of the Sub-Tatric and High-Tatric Succession	recharge from Czerwone Wierchy Massif (*ca.* 17 km^2); documented connections with Śnieżna, Czarna and Miętusia caves
Bystre (Upper and Lower)	Bystra	above 1180	descent	karst system in Triassic deposits of the High-Tatric Succession	probable recharge from Giewont Massif, connections with Bystra and Kalacka caves
Goryczkowe	Goryczkowy	above 1185	ascent	karst system in Triassic deposits of the High-Tatric Succession	recharge by karst systems from beyond the Goryczkowy Stream drainage basin, that is from the Sucha Woda drainage basin
Olczyskie	Olczyski	above 1070	ascent	outflow from rocks lying on limestones and dolomites of the Sub-Tatric Succession	recharge by karst areas from beyond the Olczyski Stream drainage basin, that is from the Pańszczycki Stream drainage basin (Sucha Woda Valley)

Table 2

Rate of drying up of Tatra vaucluse springs (by Maillet formula)

Vaucluse spring	Mean recession coefficient α [1/d]	Period for which the mean flow is assumed as Q_0	Q_0	Q_{10}	Q_{30}	Q_{60}	Q_{90}
Chochołowskie	0.017	1980–1990	421	354	251	150	89
Lodowe	0.022	1980–1990	529	423	271	139	71
Bystre	0.021	1979–1990	321	260	172	92	49
Goryczkowe	0.020	1979–1990	679	570	382	209	114
Olczyskie*	0.021	1979–1986	537	436	288	155	83

Q_t — after t-days recession in dm^3/s; * D. Małecka, W. Humnicki (1989)

CHOCHOŁOWSKIE VAUCLUSE SPRING

It is situated about 30 m south of Skała Kmietowicza in the Chochołowska Valley (Niżnia Brama Chochołowska) at about 988 m a.s.l. It flows out from beneath steep slopes composed of limestones and bedded dolomites corresponding to the lower part of the lower Sub-Tatric Succession (Middle Triassic). It occurs in form of a small lake with a characteristic funnel — shaped depression (about 1.6 m deep), from which water ascents in two streaks to the Chochołowski Stream. The main suppliers of the vaucluse spring are karst systems of the Szczelina Chochołowska–Rybia caves (T. Solicki, B. Koisar, 1973; R. Rogalski, 1984). Additionally, hydrogeologic data (R. Rogalski, 1984; G. Barczyk, 1994) point to a *ca.* 20% supply from surface waters of the Chochołowski Stream. The recharge area of the Chochołowskie vaucluse spring lies entirely within the Chochołowski Stream groundwater basin and covers about 7 km^2 (G. Barczyk, 1994, 1998).

A water-mark and limnograph has been installed in the vaucluse spring. A second water-mark is present beneath the runoff of the streams towards the Chochołowski Stream, on the level of the upper limit of the Polana Huciska.

LODOWE VAUCLUSE SPRING

It is situated on the eastern side of the Kościeliski Stream, about 50 m from a small bridge on the way to the Mroźna Cave, beneath the valley neck — Brama Kraszewskiego. It ascends from a limestone debris, about 974 m a.s.l., within the contact zone of the High-Tatric and Sub-Tatric Successions. The runoff occurs in an area of several tens of m^2, creating a small flooding, from which water flows in three arms to the stream. The Lodowe vaucluse spring dewaters the Czerwone Wierchy Massif. Colouring of karst water carried out in the 60-ties and 70-ties pointed to connections of the spring with, i.e. the Śnieżna, Czarna and Miętusia caves (T. Dąbrowski, J. Rudnicki, 1967). The vaucluse spring recharge area reaches beyond the surface boundary of the Kościeliski Stream recharge area, possibly to the south and east, covering an area of about 17 km^2 (G. Barczyk, 1994, 1998).

The Lodowe vaucluse spring and its close vicinity can be treated as a sort of a scientific "testing ground". From the mid-seventies a water-mark is present beneath the runoff of the vaucluse waters to the Kościeliski Stream as well as one in the vaucluse spring itself. Since 1989 a limnigraph is also operating in the vaucluse spring.

BYSTRE VAUCLUSE SPRINGS — UPPER AND LOWER

Both vaucluse springs occur on the western side of the Bystra Stream, about 200 m below its source. They are situated on the eastern slope of the Kalacka Turnia, 50 m below the blue tourist track to Hala Kondratowa, about 1180 m a.s.l. and they are 15 m apart. Due to a slight difference in height above sea level, the southern runoff is called the Upper, and the northern one — Lower. The latter carries water continuously, while the Upper vaucluse spring sporadically dries up. In both cases water descends from rock debris directly into the Bystra Stream. The karst system supplying water to the springs developed in carbonate deposits of the Middle Triassic and the Malm–Neocomian of the High-Tatric Succession. The direct recharge area of the springs has not been determined (J. Rudnicki, 1967). Possibly the vaucluse springs dewater the Giewont Massif and the area situated southwards (J. Gała, K. Gul, 1981; D. Małecka, 1993). In the close vicinity of both springs the Bystra and Kalacka caves are present, the Kalacka being a lower, younger level of the Bystra Cave, for which the Bystra vaucluse springs are considered a dewatering system. A water-mark is present on the Bystra Stream, about 150 m below the springs, allowing to determine their joined discharge.

GORYCZKOWE VAUCLUSE SPRING

It is situated on the northwestern slopes of the Myślenickie Turnie in the Goryczkowy Stream valley, about 1185 m a.s.l. It flows out from a wide (*ca.* 4 m) erosional depression within the stream channel. The flow has an ascending character, particularly notable during lowstands. The recharge area covers probably the karstified Myślenickie Turnie Massif, the alluvial-moraine deposits infilling the valley, as well as karst systems reaching the Sucha Woda Stream drainage basin. The main karst system representing external circulation (J. Głazek, 1995) is developed in Middle Triassic limestones of the High-Tatric Succession. Karst connections between the Goryczkowe vaucluse spring and Sucha Woda drainage basin have been proved by several colourings (T. Dąbrowski, J.Głazek, 1968; D. Małecka, 1985*a*; J. Pachla, W. Zaczkiewicz, 1981). A water-mark is present in the Goryczkowy Stream, about 50 m below the main runoff of the vaucluse spring.

OLCZYSKIE VAUCLUSE SPRING

It is situated on Polana Olczyska about 1070 m a.s.l., beneath the Skupniów Upłaz on the western side of a large pasture. Water ascends from a depression 9 m in diameter. The depression is infilled with limestone debris, sandstone and crystalline rock fragments overlying the Triassic limestones and dolomites of the Sub-Tatric Succession. The vaucluse spring is supplied by karst systems of external circulation from the Sucha Woda Valley (Pańszczyca Valley). This migration was described by A. Wrzosek (1933), and confirmed by experimental colourings in the 60-ties and 80-ties (T. Dąbrowski, J. Głazek, 1968; J. Pachla, W. Zaczkiewicz, 1981). A water-mark is present 220 m below the runoff on the Olczyski Stream.

RECESSION CURVE ANALYSIS

The determination of flow regimes and their sources as well as groundwater resourses largely depends on recession curve analysis. In the Tatra conditions, the specific climate unables a continuous observation of the recession curve (short duration of truly precipitation — free periods). On the stage discharge curve the recession curve fragments appear in different periods and are of different length. The elementary recession sections allow to construct a mean standard curve (P. Jokiel, 1987), nevertheless identification of particular sections of the hydrogram as representing the recession phase creates some difficulties. In the case of Tatra vaucluse springs, the semi-logarithmic curves method has been used (J. Pleczyński, 1981), successfully applied in mountainous conditions (W. Humnicki, 1992) in hydrogram analysis. The declining fragments of the hydrogram form in the semi-logarithmic system groups of straight lines with inclinations characteristic for every type of water creating a complete runoff from the vaucluse spring. These straight lines allow to determine the underground runoff regime for several years and creation of a standard recession curve for the discharge of an aquifer system with undisturbed conditions, described by the Maillet formula. The mean values of coefficients for particu-

Table 3

The "drying up" coefficient α_1 (after L. Radczuk, O. Szarska, 1986) and Q_B for the Tatra vaucluse springs

Period	Chochołowskie		Lodowe		Bystre		Goryczkowe		Olczyskie	
	α_1 [1/d]	Q_B [dm^3/s]	α_1 [1/d]	Q_B [dm^3/s]	α_1 [1/d]	Q_B [dm^3/s]	α_1 [1/d]	Q_B [dm^3/s]	α_1 [1/d]	Q_B [dm^3/s]
1994–1995	0.0224	287	0.1047	496	–	–	–	–	–	–
1993–1994	0.0343	223	0.7606	528	–	–	–	–	–	–
1992–1993	0.0853	326	0.4374	470	–	–	–	–	–	–
1991–1992	0.0443	260	0.1214	377	–	–	–	–	–	–
1990–1991	0.0315	233	0.1334	317	–	–	–	–	–	–
1989–1990	0.0084	126	0.2757	372	0.3715	233	0.3891	366	–	–
1988–1989	0.1893	273	0.1217	196	0.1746	168	0.0737	190	–	–
1987–1988	0.0431	249	0.0174	156	0.0559	131	0.5369	211	–	–
1986–1987	0.0123	188	0.0479	197	0.0622	122	0.1919	222	–	–
1985–1986	0.0435	248	0.1215	303	0.0997	158	0.2139	329	0.4457	434
1984–1985	0.0290	222	0.1066	203	0.0679	123	0.1160	279	0.0677	264
1983–1984	0.0527	290	0.1393	220	0.3720	142	0.2981	283	0.0369	230
1982–1983	0.1427	331	0.0800	201	0.2470	133	0.0669	232	0.0287	236
1981–1982	0.0802	249	0.1737	130	0.0146	107	0.0389	229	0.0180	216
1980–1981	–	–	0.1488	215	0.0688	131	0.0503	187	0.0918	324
1979–1980	–	–	–	–	0.0389	131	0.0466	168	0.0441	189
Average	0.0585	250	0.1860	292	0.1430	143	0.1838	245	0.1047	270
Average 1981–1990	0.0668	242	0.1204	220	0.1628	146	0.2139	260	0.1194	276

Table 4

The "drying up" coefficient α_2 (by Mangin) and Q_{RO} for the Tatra vaucluse springs

Period	Chochołowskie		Lodowe		Bystre (Upper and Lower)		Goryczkowe		Olczyskie	
	α_2 [1/d]	Q_{RO} [dm^3/s]	α_2 [1/d]	Q_{RO} [dm^3/s]	α_2 [1/d]	Q_{RO} [dm^3/s]	α_2 [1/d]	Q_{RO} [dm^3/s]	α_2 [1/d]	Q_{RO} [dm^3/s]
1994–1995	0.0009	328	0.0012	490	0.0024	185	0.0026	261	–	–
1993–1994	0.0015	270	0.0012	407	0.0029	178	0.0025	268	–	–
1992–1993	0.0014	340	0.0012	354	0.0017	191	0.0033	288	–	–
1991–1992	0.0013	281	0.0012	365	0.0023	193	0.0037	277	–	–
1990–1991	0.0029	292	0.0013	220	0.0025	145	0.0022	246	–	–
1989–1990	0.0025	339	0.0015	252	0.0027	185	0.0017	255	–	–
1988–1989	0.0017	287	0.0032	222	0.0038	192	0.0031	219	–	–
1987–1988	0.0018	287	0.0029	251	0.0019	165	0.0014	201	–	–
1986–1987	0.0011	247	0.0028	261	0.0025	169	0.0029	243	–	–
1985–1986	0.0026	303	0.0027	293	0.0029	194	0.0013	240	0.0029	256
1984–1985	0.0011	247	0.0034	200	0.0017	126	0.0019	240	0.0019	313
1983–1984	0.0019	321	0.0032	214	0.0031	168	0.0023	250	0.0018	234
1982–1983	0.0071	291	0.0031	279	0.0025	148	0.0023	264	0.0016	286
1981–1982	0.0013	235	0.0046	182	0.0026	179	0.0014	240	0.0016	299
1980–1981	–	–	0.0047	224	0.0044	180	0.0029	257	0.0015	310
1979–1980	–	–	–	–	0.0039	214	0.0034	290	0.0019	217
Average	0.0016	291	0.0026	281	0.0029	176	0.0025	252	0.0019	274
Average 1981–1990	0.0016	284	0.0031	239	0.0027	170	0.0021	239	0.0019	278

lar vaucluse springs are nearly similar (Tab. 2), what points to their similar hydrogeologic regime.

The runoff created in course of alimentary basin drainage can be also described in form of a simplified mathematic model. The model bases on the assumption that the runoff from the aquifer layer is proportional to the product between the area of the recharge cross-section and the variable decrease of the energy line (L. Radczuk, O. Szarska, 1986), as well as on the fact that the resources are continuously renewed due to basic retention (basic runoff Q_B).

The analysis of recession curves from the autumn–winter periods of Tatra vaucluse springs points to their distinct bipartition (D. Małecka *et al.*, 1985; G. Barczyk, 1993, 1994, 1997) with different angles of the curve gradient. The assumption that the steep segment may correspond to the decline curve and the gentle segment to the regression curve allows to interpret this bipartition as the existence of two alimentation areas, being, however, in contact with one another. According to this interpretation the steep segment would correspond to a local reservoir, while the gentle segment to a regional reservoir. This assumption seems perfectly correct, particularly in light of the noted karst runoffs recharging each of the vaucluse springs from distant areas. For example the local reservoir of the Lodowe vaucluse spring is the Czerwone Wierchy Massif dewatered by it. The recession α_1 and basal runoff Q_B coefficients for all noted years are presented in Table 3. Analysis of Q_B values calls attention to their distinct convergence. Mean values oscillate between 240 and 290 dm^3/s. For better comparison the mean values from periods when all the vaucluse springs were under observation have been presented in Table 3. A slight difference can be observed in the mean values for the Bystre Upper and Lower vaucluse springs, what can be explained by a particularly small rechar-

Table 5

Volumes of water stored up in local and regional groundwater reservoirs calculated by Mangin formula

Vaucluse spring	Average volume of water stored up in local groundwater reservoir [m^3]	Average volume of water stored up in regional groundwater reservoir [m^3]
Chochołowskie	478 895	17 803 757
Lodowe	2 060 085	13 321 359
Bystre	1 234 532	5 396 048
Goryczkowe	2 668 985	10 307 828
Olczyskie	3 417 397	13 059 859

ge area and a high hypsometric position. The mean Q_B values for these springs reaches about 150 dm^3/s. It has to be stated that although the vaucluse springs are situated in different parts of the Tatra Mts., the duration of the autumn– winter recession periods is similar in all cases.

RETENTION OF AREAS DRAINED BY VAUCLUSE SPRINGS

One of the interesting methods allowing to characterize the hydrodynamic conditions of a fissure-karst aquifer is the Mangin method (A. Mangin, 1975). It was successfully applied by its author to determine the hydrodynamic conditions in karst aquifers of the Pyrenees. In Poland the method was applied to selected periods for the Goryczkowe (D. Małecka *et al.*, 1985), Lodowe (M. Konowrocka, A. Piekarski, 1988; G. Barczyk, 1994, 1997) and Chochołowskie (G. Barczyk, 1994, 1997) vaucluse springs. The autumn–winter regression curves used in this method were based on the values of discharge volumes interpreted from rating curves as well as on limnigraphic observations. In the regression curve analysis of the described vaucluse springs the curves can be mathematically expressed by the Mangin equation in the following form (A. Mangin, 1975):

Table 6

Mean underground outflow $Q_{pśr}$ [dm^3/s] from the Tatra vaucluse springs

Method	Chochołowskie	Lodowe	Bystre (Upper and Lower)	Goryczkowe	Olczyskie
Wundt	323	373	208	417	380
Kille	306	345	175	301	363

$$Q = Q_{RO}e^{-\alpha t} + q_0\frac{1-\eta t}{1+\varepsilon t}$$

where: Q — expected vaucluse spring discharge during time t; Q_{RO} — value characterizing initial discharge of regional reservoir; e — radix of natural logarithm; α — regression coefficient; q_0 — value calculated from the substraction Q_0–Q_{RO} (where: Q_0 — initial discharge of local reservoir); t — time; η — parameter describing drawdown time; ε — recession curve concavity coefficient

Particular attention has to be drawn to the Q_{RO} parameter characterizing the initial discharge of the regional reservoir (Tab. 4). Following the presented interpretation of the recession curves bipartition, the parameter can be treated as a distant area, drained by vaucluse springs during the minimal recharge (winter period). The regional reservoir is therefore common for all vaucluse springs. The area recharging vaucluse springs during periods with large precipitation (from spring to autumn), separate for each vaucluse spring, can be treated as the local reservoir. In this interpretation the value of Q_{RO} would correspond to the terminal discharge, beneath which recharge takes place only from the regional reservoir. In the case of the Chochołowskie, Goryczkowe, Bystre Upper and Lower (jointly) and Olczyskie vaucluse springs the values of the terminal discharges Q_{RO} reach the mean values, where as in the Lodowe vaucluse spring they are more diverse. Similarly as in the case of the basic discharge Q_B, the absolute values of Q_{RO} for Bystre Upper and Lower vaucluse springs are much lower than for other springs.

Application of the Mangin formula allows also the estimation of water capacity within local and regional reservoirs (A. Mangin, 1975). In the Polish Tatra Mts. such calculations were carried out only for the Goryczkowe vaucluse spring (D. Małecka *et al.*, 1985). Comparison of the mean values of capacity for the particular vaucluse springs allows to note several regularities. Volumes of local reservoirs differ signi-

Table 7

Comparison between average Q_{RO}, underground outflow $Q_{pśr}$, Q_B and Q_{min} [dm^3/s]

Method	Chochołowskie (1981–1995)	Lodowe (1980–1995)	Bystre (Upper and Lower) (1980–1995)	Goryczkowe (1980–1995)	Olczyskie (1979–1986)
Values $Q_{pśr}$ calculated according to the Wundt method	323	373	208	417	380
Values $Q_{pśr}$ calculated according to the Kille method	306	345	175	301	363
Mean value of Q_{RO}	291	281	176	251	274
Basic outflow Q_B	250	292	143	245	270
Mean value of boundary discharge between the local and regional reservoir	292	323	176	304	322
Mean minimal discharge (Q_{min}) for selected periods	220	183	89	166	190

Table 8

Rate of drying up of the regional groundwater reservoir from Tatra Mts. (by Maillet formula)

Vaucluse spring	Value of boundary discharge Q_0	Q_{10}	Q_{30}	Q_{90}	Q_{180}	Q_{365}	Q_{730}
Chochołowskie	292	281	259	205	143	69	16
Lodowe	323	310	286	226	158	76	18
Bystre	176	170	157	124	87	42	10
Goryczkowe	304	297	274	216	151	73	17
Olczyskie	322	309	285	225	158	76	18

Q_t — after t-days recession in dm^3/s

ficantly depending on the vaucluse spring. The smallest capacity of water — *ca.* 479 000 m^3 — contains the reservoir dewatered by the Chochołowskie vaucluse spring. This is in line with the statement that the recharge area of this vaucluse spring occurs entirely within the Chochołowski Stream drainage basin and comprises only karst systems within carbonate deposits (Fig. 1). Similar to results calculated from the Mangin formula are those presented by R. Rogalski (1984) for the Chochołowskie vaucluse spring while carrying out tracer investigations in the spring (capacity of water in the reservoir — about 580 000 m^3). The Bystre vaucluse springs are also recharged from a small area, therefore the water capacity in the local reservoir is rather small (*ca.* 1 234 000 m^3). The Lodowe and Goryczkowe vaucluse springs have much larger recharge areas. Volumes of water accumulated in these reservoirs are similar. The largest amounts of water (*ca.* 3 400 000 m^3) are accumulated in the Olczyskie vaucluse spring reservoir, the alimentation area reaches far beyond the boundaries of the Olczyski Stream recharge area, that is to the Pańszczyca Valley.

In the case of water volumes accumulated in regional reservoirs the values for particular vaucluse springs (with the exception of the Bystre vaucluse springs) do not reveal such differences. A slightly higher value for the Chochołowskie vaucluse spring can be a result of a partial recharge of the spring by surface waters of the Chochołowski Stream (Tab. 5).

GROUNDWATER RUNOFF

The method of hydrograph genetic subdivision, that is the method of wave truncation is most frequently used to evaluate groundwater runoff (M. Gutry-Korycka, 1978; I. Dynowska, 1974, 1979). In the Tatra area, in the case of frequently occurring high water waves, subdivision of the hydrograph, principally subjective, arouses some doubt. Therefore the A. Wundt (1958) and K. Kille (1970) methods have been used in the analysis of stationary observations of the Tatra vaucluse springs. In the Wundt method the mean low monthly runoff is supposed to represent the underground runoff. The Kille method is also interesting, creating a separating order of minimal monthly discharges, and then including arranged values in the co-ordinate system. The value of mean underground runoff corresponds then to the value of the ordinate equal to the middle of the abscissa axis. This method usually gives values lower than the Wundt method (I. Dynowska, 1979). Mean underground runoff values for particular vaucluse springs are presented in Table 6.

In both methods the obtained results are more or less similar and reach values of 300–400 dm^3/s for most vaucluse springs. As in the case of the Q_B and Q_{RO} values, the results for the Bystre Upper and Lower vaucluse springs are lower, reaching *ca.* 200 dm^3/s. The obtained results testify for the fact that values in the Kille method are generally lower. Naturally in the vaucluse springs we deal exclusively with groundwaters. Therefore the obtained $Q_{p\acute{s}r}$ values should correspond, similarly as in the case of the Q_B and Q_{RO} values, to the boundary values between recharges of combined regional and local reservoirs and between recharge exclusively from the regional reservoir, taking place after the detachment of the local reservoir.

BOUNDARY DISCHARGES BETWEEN LOCAL AND REGIONAL RESERVOIRS

Tatra vaucluse springs are characterized by the existence of two recharge areas co-operating with one another — a local, separate for each vaucluse spring and a regional one recharging vaucluse springs during low-flow periods. The evaluation of the boundary values, at which the local reservoir is detached, is an interesting investigation problem. Comparing mean values of boundary discharges Q_{RO} (Tab. 4), with calculated values of mean underground runoff (Tab. 6) and basic discharge Q_B (Tab. 3) their distinct convergence can be observed (Tab. 7).

The convergence is in line with the suggestion of a combined regional groundwater reservoir occurrence, covering the whole Tatra Massif area (D. Małecka, 1993). The isolation of some aquifers, occasionally noted by karst workers, has probably a local meaning. In general all types of water are in hydraulic connection. The boundary values applied for recharge only from this regional reservoir should reach a discharge of *ca.* 300 dm^3/s. Of course this value is not definite and the same for each vaucluse spring. For particular springs the discharge interval reaches 300–285 dm^3/s for the Chochołowskie, 330–310 dm^3/s for the Lodowe, Goryczkowe and Olczyskie and 185–170 dm^3/s for the Bystre Upper and Lower vaucluse springs. Within these intervals the recharge from regional and local areas passes into recharge from local areas (Tab. 7). At this assumption after 30 days of recession almost all investigated vaucluse springs will drain the regional reservoir (Tab. 2).

REGIONAL RESERVOIR RECESSION CURVE

Analysis of the hydrogeological regime of the vaucluse springs during draining of regional reservoir represents another problem. The gentle segments of recession curves of particular vaucluse springs (Tab. 2) are similar. Each curve can be described by a specific formula — in the case of the described recession curves the best formula is the straight line formula $Y = AX + B$. For particular vaucluse springs this gives groups of straight lines with similar parameters A and B. Mean general formulas of regional reservoir recession curves for particular vaucluse springs are as follows:

— Chochołowskie: $Y = -1.12X + 302.3$

— Lodowe: $Y = -1.14X + 263.3$

— Bystre (Upper and Lower): $Y = -0.85X + 204.0$

— Goryczkowe: $Y = -1.03X + 254.6$

— Olczyskie: $Y = -1.05X + 266.4$

Similarities of the curves are distinct. Assuming the occurrence of a regional reservoir, drained in deep low-flow periods by all vaucluse springs, the theoretic calculation of a general recession curve for this reservoir is possible: $Y = -1.04X + 258.2$

The recession coefficient calculated from the Maillet formula for this curve equals 0.0039 (Tab. 8). The drying up velocity of reserves of a such defined reservoir is rather low. The recession coefficient value is much lower compared to values calculated for particular vaucluse springs (Tab. 2). It has to be stated, however, that values of the recession coefficient α in Table 2 were calculated for discharge during periods of recharge from local and regional reservoirs, and not exclusively from the regional reservoir.

CONCLUSIONS

The presented calculations allow to make several statements:

— Tatra vaucluse springs are characterized by specific bipartite recession curves;

— each vaucluse spring drains a local as well as a regional reservoir;

— values of particular vaucluse spring recharges, at which the draining of exclusively the regional reservoir starts, are quite similar, they vary between 300 dm^3/s for the Chochołowskie, Lodowe, Goryczkowe and Olczyskie vaucluse springs and *ca.* 200 dm^3/s for the Bystre Upper and Lower vaucluse springs;

— after 30 days of recession most vaucluse springs are drained by the regional reservoir;

— segments of recession curves corresponding to the drained regional reservoir are similar for all vaucluse springs, approximated by straight lines of the $Y = AX + B$ type with similar parameters;

— volumes of water stored in regional reservoirs of particular vaucluse springs are more or less similar;

— regional reservoirs drained by particular vaucluse springs are possibly in connection with each other, what suggest the existence of one reservoir common for all vaucluse springs;

— drying up velocity of reserves in the common regional reservoir is rather low.

Future stationary observations of the described vaucluse springs will help to determine the presented results more precisely, as well as solve other problems connected with the dynamics of Tatra vaucluse springs, such as reaction to precipitation, dependence of time of discharge from recharge areas to vaucluse springs to the watering conditions of the massif, as well as others.

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WYBRANE PARAMETRY HYDROGEOLOGICZNE DLA WYWIERZYSK TATRZAŃSKICH

Streszczenie

W artykule poddano analizie wyniki dwudziestoletnich obserwacji stacjonarnych wydajności pięciu największych wywierzysk krasowych Tatr Polskich. Interpretacja krzywych wysychania, przy zbliżonych wartościach współczynników regresji, pozwoliła wysnuć wnioski o zbliżonym reżimie hydrogeologicznym wszystkich wywierzysk tatrzańskich. Stwierdzoną wyraźną dwudzielność krzywych można interpretować jako istnienie odrębnych, lecz pozostających ze sobą w kontakcie hydraulicznym, zbiorników wód podziemnych: lokalnego i regionalnego.

Zastosowanie formuły Mangina pozwoliło na oszacowanie objętości wód zmagazynowanych w zbiornikach lokalnych i regionalnym, w odniesieniu do poszczególnych wywierzysk. Wyznaczono również kilkoma metodami wielkość wydatków granicznych poszczególnych wywierzysk, przy których kończy się drenowanie zbiorników lokalnych i regionalnego, a rozpoczyna drenaż wyłącznie zbiornika regionalnego. Stwierdzono niewielką prędkość sczerpywania zasobów wód podziemnych w odniesieniu do wspólnego zbiornika regionalnego.