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Dependence of karst denudation on geological structure in the SW part of the Holy Cross Mts (Central Poland)

ABSTRACT: The chemical analyses of karst waters in the SW part of the Holy Cross Mts, carried out at different months, have revealed seasonal variation; they have also enabled to calculate the index of karst denudation and establish the dependence of their composition on lithology of soluble formations. It appeared that the karst denudation of Devonian dolostones is several times greater than that of the Devonian and Triassic limestones. The high SO_4^{2-} and Cl^- content in Devonian dolostone waters suggests a hypersaline environment during dolomite sedimentation. Moreover, a discussion is given on the denudation index, on the errors in its calculation and on the geomorphological significance of this index.

INTRODUCTION

The SW part of the Holy Cross Mts is a remarkable area for studying the dependence of the chemical composition of karst waters and karst denudation on geological structure. Karst phenomena of the region were the subject of several papers (*e.g.* Majchert 1966¹), dealing mainly with caves (*cf.* Wołoszyn & Wójcik 1965¹). The fragmentary data on various karst phenomena are also to be found in some general papers (*e.g.* Gilewska 1964¹; Głazek, Dąbrowski & Gradziński 1972; Hakenberg & Lindner 1971) whereas the chemical composition of karst waters has not hitherto been studied.

Between 1966 and 1972 the present writers have made hydrological and hydrochemical observations (*cf.* Głazek & Markowicz-Łohinowicz 1973¹) during which the water samples were taken the year round in order to seize the seasonal variation of the chemical composition of karst

¹ Papers with a comprehensive regional bibliography.

waters (cf. Douglas 1964) and its dependence on the lithology of the soluble formations. For comparison a study was made of the results of some tens of water analyses from wells at Chęciny, carried out by the SANEPID of Kielce². These analyses were used specially for estimation of water pollution.

The method used in the authors' investigation was the standard chemical volumetric method (cf. Konovalov 1962, Höll 1970); also the hydrochemical karst water classification worked out by one of the authors for the vicinity of Częstochowa in the Polish Jura Chain (cf. Markowicz-Łohinowicz 1968, 1973; cf. also Figs 1 and 4) was applied.

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GEOLOGICAL CONDITIONS OF KARST WATER CIRCULATION

Within the area considered, karst phenomena develop within the occurrence zones of several formations (Fig. 1) which may be shortly characterized as follows.

The Devonian dolostones referred to the Eifelian and Givetian (cf. Czarnocki 1938) are the oldest soluble formations. In the lower part of the sequence these are micritic, probably primary dolostones which pass upwards into sparry, strongly jointed and porous dolostones. Karst water circulation exists in these dolostones but major karst forms are very rare.

The largest caves and all the so far paleontologically dated karst forms occur in the lower parts of the Devonian limestones referred to the Givetian through the Famennian. In the lower parts of the profile these are pure, thick-bedded biosparites passing upwards into thin-bedded marly limestones.

Karst topography is but poorly developed within the Zechstein limestones and limestone conglomerates, but numerous small karst forms occur in the Röt and Muschelkalk carbonates. These are platy and fine-platy micritic and detrital limestones, intercalated by marly limestones and marls limiting the development of the karst forms.

A major soluble formation is represented by the Upper Jurassic limy deposits of the Oxfordian and Kimmeridgian. These are platy, chalky, batten and oolitic limestones, in the top (higher part of the Lower Kimmeridgian) passing into marls. In the limestones there exist numerous poorly recognized karst forms.

In the profile the diverse soluble formations in the Holy Cross Mts are separated by insoluble formations, as a rule, impermeable (shale, clay and marl). The block-fold structure (Kutec & Głazek 1972) resulted in the formation of isolated tectonic blocks leading to numerous local karst water circulation systems confined to the soluble formations within the particular tectonic blocks (Figs 1—3).

Since their Tertiary evolution into a distinct geomorphological unit the Holy Cross Mts have never been a high mountain chain (cf. Kutec & Głazek 1972). The

² SANEPID — State Sanitary Epidemiological Survey for the Kielce District.

circulation systems now active in the soluble rocks within the area under consideration are not older than Upper Miocene, and, very probably, most of them may be dated as Quaternary. The lowermost karst water table occurred at the level of river

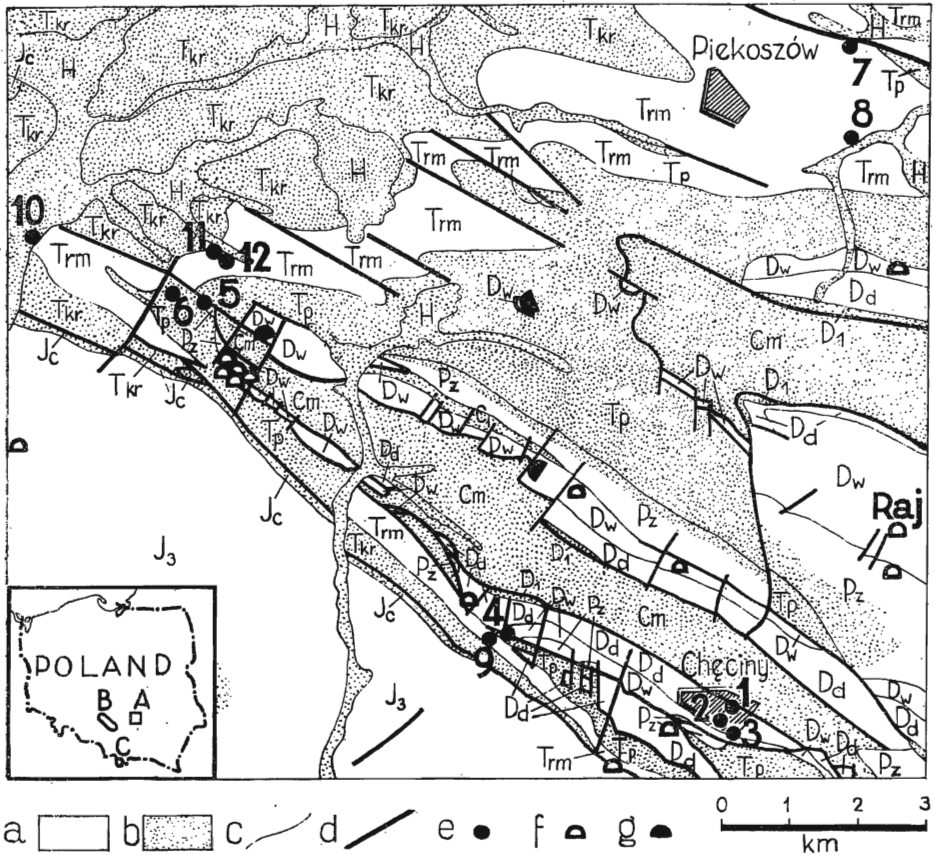


Fig. 1

Geological map of the investigated area (after Czarnocki 1938, modified); inset shows position of the investigated (A) and compared regions (B Polish Jura Chain, C Western Tatra Mts)

a soluble rocks, b insoluble rocks, c stratigraphic boundaries, d faults, e investigated wells (1–3) and sources (4–12), f caves, g ponors

Stratigraphic division: Cm Cambrian (shales and sandstones), D₁ Emsian (sandstones), Dd Eifellian-Givetian (dolostones), Dw Givetian-Famennian (limestones), C₁ Lower Carboniferous (shales with subordinate limestone intercalations), Pz Zechstein (conglomerates, limestones, marls and shales), Tp early Bunter (shales and sandstones), Trm Röt and Muschelkalk (limestones and marls), Tkr Keuper and Rhaetian (shales, clays and sandstones), Jo Callovian (detrital cherty limestones), J₃ Oxfordian-Kimmeridgian (limestones and marls), H Holocene (sands, clays and peat)

valley bottoms now buried under Pleistocene sediments (c. 60 m below their present level). The variability of the karst water tables showing a range of up to 100 m occurred during the Pleistocene as a result of climatic changes and the resulting repeated periods of the burial of valleys (cf. Różycki 1967, Hakenberg & Lindner 1971).

At present, as a result of the removing of Pleistocene deposits from the valleys, there progresses a lowering of the karst water table and a knick-point recession (cf. Warwick 1960), on the surface as well as underground. Over the last 50 years this process has accelerated owing to human activity (deforestation, unsound melioration and intensive exploitation of underground waters). Within karst regions, this process causes the activation of fossil karst forms buried under loose and permeable Quaternary sediments.

The type of karst water table occurring in the fragments of the area under consideration, built of carbonate rocks, is that of a *nappe en réseau* (cf. Gèze 1965). Most of the water samples taken for analyses from local karst-water-circulation systems come from the shallow phreatic zone or from vadose flow (cf. Thraikill 1968).

The geological conditions of karst water circulation suggest that the chemical composition of the collected samples may probably be regarded as being representative for the particular soluble formations (Głazek & Markowicz-Łohinowicz 1973).

KARST HYDROGRAPHY

In the investigated region (cf. Fig. 1) the areas built of soluble formations lack a constant system of surface drainage. Small constant surface flows occur only where carbonate rocks are overlaid by impervious clays and Pleistocene silts.

On elevations where the carbonate rocks are exposed, the bulk of precipitation waters is absorbed by fissures, as a rule broadened by karst activity. Because the Pleistocene sediments cover the soluble rocks in valley bottom and slopes, the distinct ponors are extremely rare (cf. Głazek & Markowicz-Łohinowicz 1973, also Fig. 1).

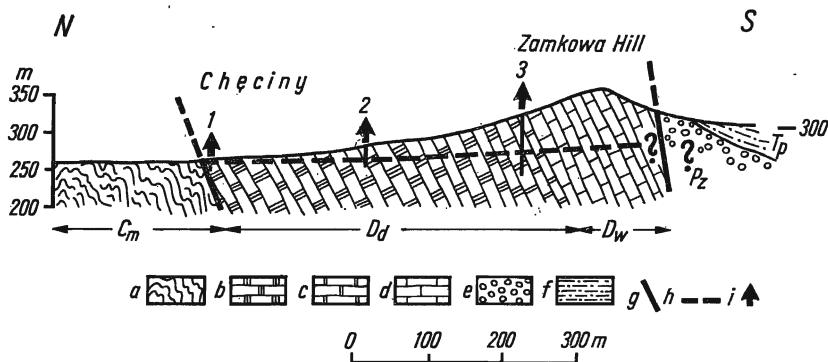


Fig. 2

Geological section showing situation of the wells at Chęciny

a strongly folded shales and sandstones, b red-brown micritic dolostones, c brown spary dolostones, d limestones, e conglomerates, f shales and sandstones, g faults, h piezometric water table, i wells

Stratigraphic symbols and numbers of wells the same as in Text-fig. 1

Quarries in carbonate formations, with the exception of the deepest ones descending below the karst water table, are dry, the waters collected there being drained by a system of fissures widened by karst activity.

The position of investigated springs and wells is marked on the map (Fig. 1). Their numbers are given according to the age of the soluble formations from which the waters emerge (cf. Głazek & Markowicz-Ło-hinowicz 1973); moreover, some drainage systems are illustrated in sections (Figs 2 and 3).

The exsurgences occur along lithostratigraphic boundaries (Nos. 9 and 11) or fault boundaries (Nos. 4, 5 and 7) between the carbonate and the insoluble formations, also along boundaries of carbonate rocks with the Pleistocene sediments filling up the deep valleys. In the latter case, these exsurgences occur in the hypsometrically lowermost points within occurrence zones of tectonic blocks built of soluble formations, and often they issue from a thin cover of Quaternary sands (Nos. 4, 8, 12). Exsurgences Nos. 7 and 10 flow out of broad fissures. A constant spring (point No. 6) flowing out of the Bunter has been examined for comparison.

Within the Devonian dolostone outcrop zone the absence is now noted of springs until recently observable at Chęciny on the Devonian dolostones/Cambrian shales boundary (Majchert 1966) and which have subsequently vanished due to water pumping from wells (cf. Fig. 2). In other parts of the area the absence of springs at the boundary of dolostone outcrops is caused by water outflow through limestones towards younger deposits at the limbs of the Chęciny anticline (cf. Fig. 3a). In the wells

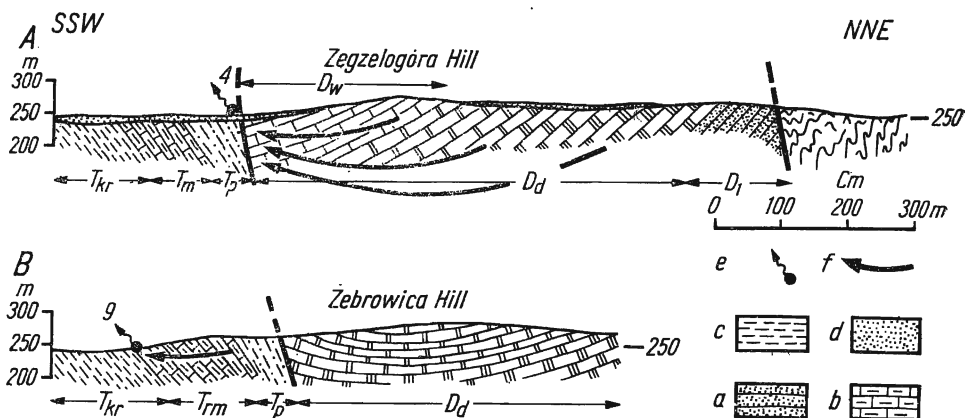


Fig. 3

Schematic sections showing situation of the resurgences no. 4 (A) and 9 (B)

a sandstones, b limestones and marls, c shales, clays and sandstones, d Quaternary sands, e exsurgences, f supposed flow line; other explanation the same as in Text-figs 1 and 2

at Chęciny seasonal considerable fluctuations of the water level and of bacteriological pollution were observed. This indicates that the wells are supplied with water from a shallow phreatic zone and vadose flow.

CHEMICAL ANALYSES AND THEIR INTERPRETATION

Results of analyses

The chemical analyses of water were done in the field, within 24 hours from the sampling time. This prevented its changing under conditions differing from its natural environment, moreover, the measurement of pH and that of the free carbon dioxide in water was carried out directly on the sampling site.

Douglas (1964) pointed out that the concluding upon a single chemical analysis of water may lead to errors caused by seasonal variability. For a more proper seize of seasonal pattern of water chemistry, the sampling was done during the low wintry (March 1970) and autumnal (October 1970) ground water level, during spring thawing (April 1970) and finally in mid-summer time (July 1969 and 1970). As results from the analyses, the maximum total hardness coincides with periods of low ground water level, while the maximum carbonate hardness in most cases occurs in spring and summer, i.e. at the beginning and development of the vegetation, under an increase in the production of biogenic carbon dioxide in the soil and in the lowest atmospheric stratum (cf. Ek 1969).

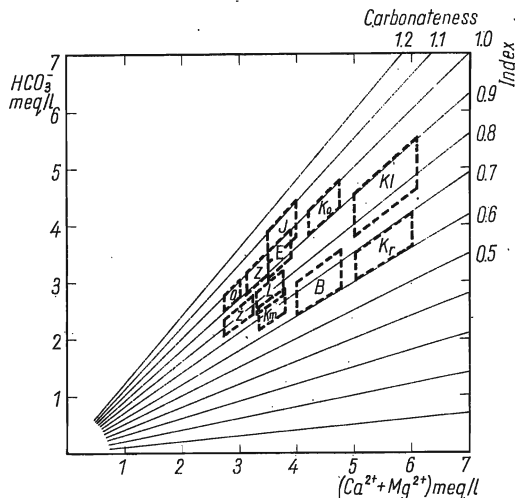


Fig. 4

Seasonal variation in hardness of karst waters from the Oxfordian limestones in the vicinity of Częstochowa, Polish Jura Chain (after Markowicz-Łohinowicz 1972). Dash-limited fields mark scopes of variations of chemical composition of karst waters from the sources (B Bzów, E Elżbieta, J Julianka, Km Karnyk, Kl Klucze, Ko Kołaczów, Kr Kromołów, L Leśniów, O Ostrężnik, Z Zygmunt, Ż Żarki); each source analysed over a dozen times during a few years in different seasons

During her studies of the chemical composition of karst water in the vicinity of Częstochowa, the fellow author (Markowicz-Łohinowicz 1973; cf. also Fig. 1) has observed that the seasonal fluctuation in carbonate hardness and total hardness is relatively constant and characteristic of the particular exsurgences. Moreover, the relation of the carbonate hardness to the total hardness in seasonally sampled exsurgence fluctuates in a relative narrow scope and that it may represent an index character of that exsurgence called the carbonateness index (Fig. 4).

The seasonal fluctuations of carbonate hardness and total hardness in karst waters of the SW part of the Holy Cross Mts have been analogously shown (Fig. 5). A comparison of the two diagrams reveals that the range of the hardness of karst waters within the vicinity of Częstochowa (from 2.7 to 6.0 meq/l $\text{Ca}^{2+} + \text{Mg}^{2+}$ and 2.6 to 5.5 meq/l HCO_3^-) is narrower than that within the SW part of the Holy Cross Mts (from 3.2 to 14.0 meq/l $\text{Ca}^{2+} + \text{Mg}^{2+}$ and from 2.2 to 11.0 meq/l HCO_3^-). This suggests that such diagrams are useful both for a comparative description of hydrochemical water samples taken from a definite karst area as well as of those collected from various karst regions. The here given differences in the hardness of waters from the vicinity of Częstochowa may be explained by the infiltration of precipitation waters into one formation only — the Upper Jurassic limestones the chemical composition of which is relatively poorly differentiated. In the limestones, these waters form one regional groundwater table where intermixture of the

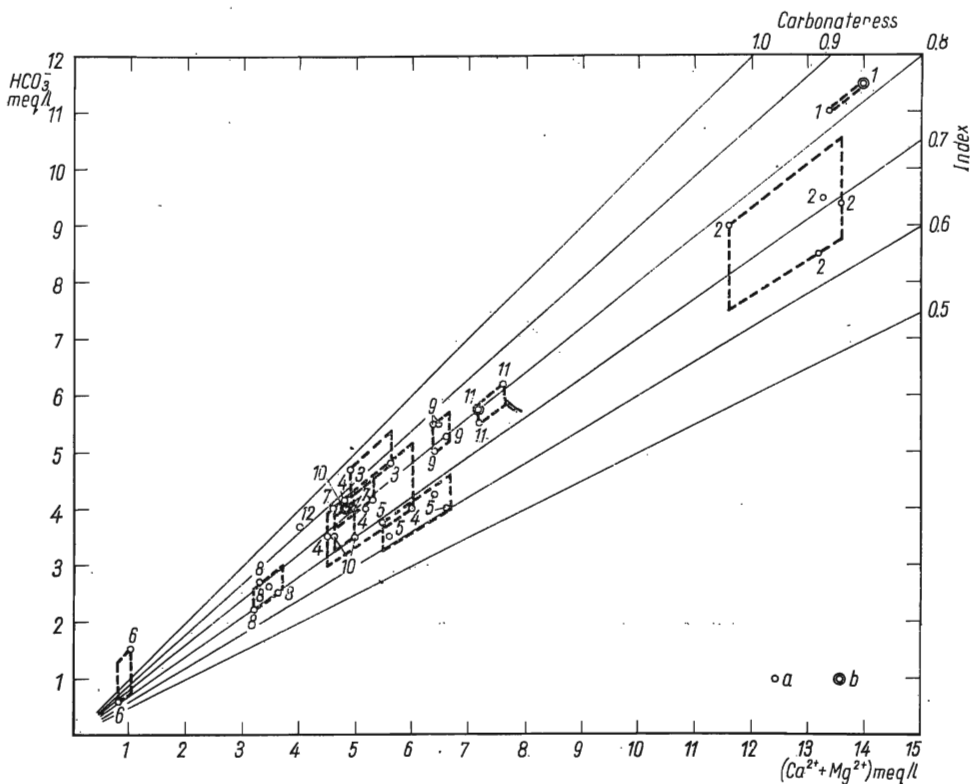


Fig. 5

Seasonal variation in hardness of karst waters in the SW part of the Holy Cross Mts
 a single analysis, b two analyses; numbers denote sources and wells the same as in Text-fig. 1

different water types has been observed. Whereas the SW part of the Holy Cross Mts is characterized by the presence of numerous local karst circulation systems in the various rocks, it causes greater differences of hardness in the here investigated sources.

The maximal seasonal fluctuations in hardness is noted in waters flowing from the Devonian (sampling sites Nos. 2 and 4) and Zechstein (site No. 5) deposits. This may suggest a wide-fissure karst circulation or a seasonal inflow of waters from another formation.

Seven out of the twelve points in the diagram (Fig. 5) showing the maximum values of the carbonateness index represent the samples taken in April. This may be explained by an increase of the biogenic carbon dioxide content in percolating waters.

The chemical composition of karst waters from the SW part of the Holy Cross Mts is shown in a diagram (Fig. 6) by mean of the percent ratio of the HCO_3^- and $\text{Ca}^{2+} + \text{Mg}^{2+}$ equivalents in the total mineralization. The slanting lines in this

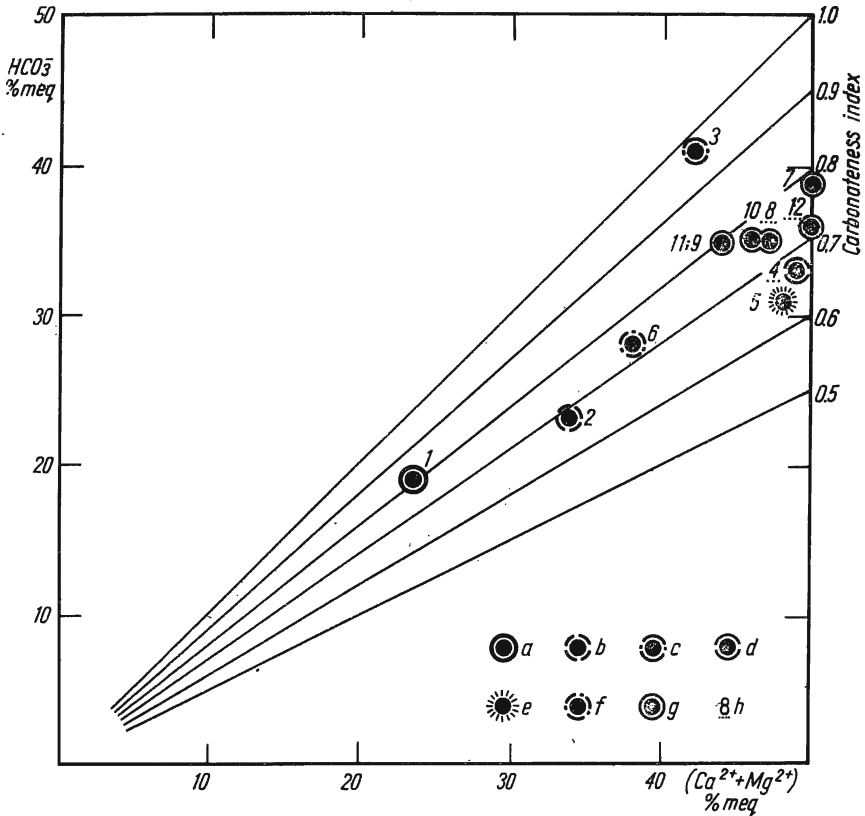


Fig. 6

Chemical composition of karst waters in the SW part of the Holy Cross Mts in October 1969

Provenience of water: a Eifelian dolostones, b Givetian dolostones, c Givetian dolostones and limestones, d Givetian limestones and dolostones, e Zechstein conglomerates, f Bunter shales and sandstones, g Muschelkalk limestones and marls, h exurgences passing through the Quaternary deposits

Numbers denote sources and wells the same as in Text-fig. 1

diagram, similarly as in the preceding one (Fig. 5) represent the isolines of the carbonateness index value (cf. Markowicz-Łohinowicz 1973). The lower value of this index, the greater noncarbonate hardness, i.e. the greater content of the sulfate and chloride salts of calcium and magnesium. As is shown in the percent composition of karst waters (Fig. 6), the greatest deviation from the standard carbonate waters is observed in samples from sites 1 and 2 (Eifelian and Givetian dolostones) and site 6 (impermeable Bunter deposits).

Since both, strongly and poorly mineralized waters may have a similar percent composition, it is convenient to compare by graphs the chemical characters of waters from various sources by the simultaneous use of both diagrams. The fields in the first diagram (Fig. 5) inform on the range of seasonal fluctuations in the hardness of water, while the points in the second one (Fig. 6) show the chemical type of water from the particular source.

The samples, the chemical composition of which is shown in the diagram (Fig. 6) have been collected during the low autumnal water level, i.e. at the time of one of the maximum water mineralization periods in the annual cycle (the other mineralization maximum occurs during the low hibernal water level preceding the thawing period). At the time of low water level and of maximum mineralization, the chemical composition of waters from karst exurgences is most characteristic of geological formations infiltrated by precipitation waters.

Hydrochemical characters of the waters

The karst waters from the springs here considered may be divided into several groups (cf. Table 1 and Figs 5—6). The strongest mineralization is observable in waters from Devonian dolostones, most particularly from their stratigraphically lower part (cf. well No. 1). A strong, non-carbonate hardness, resulting from a fairly high SO_4^{2-} and Cl^- ions content, is another significant character of these waters. The high content of these ions cannot be explained exclusively by pollution, since numerous analyses carried out by the SANEPID show only time to time bacteriological pollution and the presence of $(\text{N})_{\text{NH}_4}$ and $(\text{N})_{\text{NO}_2}$, with relatively constant, high concentration of SO_4^{2-} and Cl^- (comparable to those observed by the present writers). The water analyses from several other wells, the water of which comes from the Devonian dolostones at Chęciny indicate similar SO_4^{2-} and Cl^- ion content (about 10 meq/l).

Rather lower mineralization exhibits the water from the water-supply well at Chęciny, pumping the water from the top part of dolostones and possibly also the water seeping from limestones into dolostones (cf. Fig. 2). A comparison of the analyses, carried out during the time of maximum wintry hardness in 1962, with that carried out after the thawing period in 1970, indicates a distinctly increased mineralization. This phenomenon may be explained by the inflow of deeper, more mineralized waters, during the exploitation of the well. It is interesting to note the now and then occurrence of bacteriological pollutions in this well, too, though the concentration of the SO_4^{2-} and Cl^- ions does not display any coinciding fluctuations.

Fairly strong mineralization is observable in waters supplied from the Devonian and Muschelkalk limestones and Zechstein conglomerates. The waters from the Zechstein and the Upper Muschelkalk rocks as well as from the Devonian limestones display a higher percent content of the chloride and sulfate ions than the waters from the Lower Muschelkalk limestones, while the total mineralization of the former is but slightly stronger.

*Dependence of chemical composition of karst waters
on geological structure*

Essential relationships between the chemical composition of the investigated waters and the lithology of drained formations were observed. The strong chloride and sulfate mineralization of waters from the Devonian dolostones is probably due to a rather high content in these sediments of soluble chloride and sulfate minerals. The presence of minerals belonging to these groups has not so far been reported from the Devonian dolostones of the Holy Cross Mts (cf. Czerwiński 1960). The presence of sulfates and chlorides in the Devonian dolostones formation indicates its lagoonal environment, of the "restricted facies" type, developed in a transgressive cycle after deposition of Lower Devonian sandy deposits and before wholly marine

Table 1

Results of investigations of sources and wells in the SW part of the Holy Cross Mts

Locality of sampling and formation drained	Order of discharge l/s	Date	Water temperature °C	Ion contents meq/l						Ca:Mg ratio	Average mineralization		Carbonate denudation mm/1000 yr	Total karst denudation mm/1000 yr
				Ca ²⁺	Mg ²⁺	TH	HCO ₃ ⁻	Cl ⁻	SO ₄ ²⁻		CaCO ₃ ppm	total ppm		
				5	6	7	8	9	10		11	12		
1. Ded	-	29.10.69	11.0	11.3	2.7	14.0	11.5	11.0	8.0	4.2	573	1935	46	147
		5.03.70	-	9.6	4.4	14.0	11.5	9.5	-	2.2				
		6.04.70	5.5	10.4	3.0	13.4	11.0	-	3.5					
2. Dgd	-	18.07.69	11.2	8.0	5.3	13.3	9.5	7.2	3.7	1.5	450	870	36	70
		29.10.69	9.6	7.6	6.0	13.6	9.4	7.0	3.6	1.3				
		5.03.70	-	7.2	6.0	13.2	8.5	6.8	3.6	1.2				
6.04.70	7.9	7.2	4.4	11.6	9.0	6.4	3.2	1.7						
3. Dgd/Dgw	-	7.01.62 [*]	-	-	-	4.9	4.7	0.25	0.6	-	240	325	19	26
		6.04.70	2.5	4.0	1.6	5.6	4.8	0.5	1.0	2.5				
4. Q/Dgw/Dgd	25-50	15.07.69	9.2	1.8	3.4	5.2	4.0	0.5	1.2	1.9	200	307	16	24
		29.10.69	9.3	3.2	2.8	6.0	4.0	0.5	1.6	1.2				
		5.03.70	-	2.8	1.8	4.6	3.5	0.4	1.2	1.6				
		7.04.70	9.2	3.1	1.7	4.8	4.2	0.35	1.2	1.8				
5. Pz	0-5	28.10.69	9.1	5.7	0.7	6.4	4.25	1.3	1.2	8.1	200	350	16	28
		4.03.70	6.2	6.0	0.6	6.6	4.0	1.4	1.2	10.1				
		6.04.70	8.5	5.2	0.4	5.6	3.5	1.0	1.4	13.0				
		11.07.70	10.2	5.5	n.d.	5.5	3.75	1.0	1.25	-				
6. Tp	2-5	4.03.70	7.9	0.8	n.d.	0.8	0.6	0.25	0.2	-	50	55	4	4
		6.04.70	8.6	0.8	0.2	1.0	1.5	0.4	0.2	4.0				
7. Tpr	25-50	28.10.69	9.6	4.0	1.3	5.3	4.15	0.8	0.4	3.1	200	275	16	22
		4.03.70	8.9	3.2	1.4	4.6	4.0	0.4	1.0	2.3				
		6.04.70	8.7	4.0	0.8	4.8	4.0	0.6	0.5	5.0				
		11.07.70	9.5	3.2	1.2	4.9	4.0	0.5	0.6	2.7				
8. Q/Tm ₁	5-10	28.10.69	8.7	3.45	n.d.	3.45	2.6	0.45	0.65	-	125	232	10	19
		4.03.70	9.0	3.0	0.2	3.2	2.2	0.4	0.7	15.0				
		6.04.70	9.0	3.1	0.2	3.3	2.7	0.4	0.8	15.5				
		11.07.70	9.3	3.2	0.4	3.6	2.5	0.5	2.0	8.0				
9. Tm ₃	2-5	15.07.69	9.6	4.8	2.0	6.8	5.5	0.45	1.8	2.4	260	390	21	31
		29.10.70	9.3	5.45	1.15	6.6	5.25	0.5	1.8	4.7				
		5.03.70	-	4.8	1.4	6.2	5.0	0.3	1.2	3.4				
		7.04.70	8.8	5.0	1.4	6.4	5.5	0.3	1.0	3.6				
10. Tm ₃	5-10	28.10.69	9.8	3.8	0.8	4.6	3.5	0.5	1.0	4.7	185	296	15	24
		4.03.70	9.7	4.0	0.8	4.8	4.0	0.4	0.4	5.0				
		11.07.70	9.8	4.0	1.0	5.0	3.7	0.35	1.4	4.0				
11. Tm ₃	3-6	28.10.69	9.8	5.6	1.6	7.2	5.75	0.7	1.8	3.5	290	376	23	30
		4.03.70	9.3	5.8	1.4	7.2	5.5	0.55	1.8	4.1				
		6.04.70	9.4	6.0	1.6	7.6	6.2	0.5	2.2	3.7				
		11.07.70	9.8	3.2	4.0	7.2	5.75	0.5	2.0	0.8				
12. Q/Tm ₃	0-5	28.10.69	9.2	3.2	0.4	3.6	3.6	0.35	trace	8.0	180	192	14	15

* Analysed by the SANEPID Station at Klelce.

Formations drained: *Ded* Eifelian dolostones, *Dgd* Givetian dolostones, *Dgw* Givetian limestones, *Pz* Zechstein carbonate conglomerates, *Tp* Bunter sandstones and siltstones, *Tpr* Röt limestones and marls, *Tm₁* Lower Muschelkalk limestones and marls, *Tm₃* Upper Muschelkalk limestones and marls, *Q* Quaternary sands. Composed symbols mark complicated situation, e.g. *Dgd/Dgw* — water emerging through the Givetian dolostones from the Givetian limestones

conditions of the younger Devonian. This origin of the Eifelian dolostones has already been suggested by Czerwiński (1960). An analogous situation exists within the area east of the Holy Cross Mts, where anhydrite beds occur in Lower and Middle Devonian dolostones (Zelichowski 1972).

Fairly strong mineralization is also observable in waters from the Muschelkalk, Röt and Zechstein rocks. The hydrochemical differences in this group are controlled by lithological variability of the soluble formations and by the local hydrogeological regime. Water samples from spring No. 5 (flowing out from Zechstein conglomerates) show an increase in the chloride and sulfate ions content, samples from springs No. 4 (Devonian dolostones) and Nos. 9—11 (Muschelkalk limestones) show a higher sulfate content. Within the Zechstein deposits this phenomenon is controlled by the probable presence of rather small admixtures of chloride and sulfate salts, while in the Devonian and the Middle Triassic limestones, it depends on the admixture of sulfate salts. These, easier soluble salts have not been discovered during the investigations of surface sediments, but underneath they may continue to occur and to be dissolved in karst waters, while on the surface they had long ago been completely washed out. This interpretation is reliably suggested by the presence of gypsum intercalations in the Zechstein deposits (Szaniawski 1965), as well as by results of some analyses of Devonian limestones.

The relatively "low mineralization" of waters from the carbonate Muschelkalk formation in springs Nos. 8 and 12, similarly as a none too high mineralization of waters from the Devonian limestones (spring No. 4), may be due to a rather abundant water supply from the overlying Quaternary deposits. The direct inflow into the soluble formations of surface waters in the vicinity of springs may have reduced the mineralization of water in springs Nos. 5, and 10. This is suggested by the strong fluctuations within these springs in the mineralization and temperature of the water, similarly as in the mentioned above case of springs flowing from below Quaternary deposits (springs Nos. 4, 8 and 12).

The lowest value of the Ca : Mg index (1.2—1.6; Table 1) is observed in water samples from well No. 2 and spring No. 4. This is justified by the geological regime of these sites (Figs 2—3) since the precipitation waters reach the phreatic zone by seepage through a system of fissures in the dolostones.

A comparison of the chemical composition of karst waters from the various formations in the Holy Cross Mts (Fig. 5) with that of the karst waters from the vicinity of Częstochowa (Fig. 4) circulating in the Oxfordian limestones, reliably indicates to what extent the stronger lithological differentiation of the soluble rocks in the Holy Cross Mts causes the increased differentiation in the chemical composition of karst waters.

CHEMICAL KARST DENUDATION

Remarks on the computation methods of the karst denudation index and its significance

Among the many attempts of quantitative determination of the karst denudation rate (e.g. Rodinov 1949, Corbel 1959, Bögli 1960, Bauer 1964, Coward 1971, Howard 1971; cf. also Gvozdetsky 1972) the only method proposed by J. Corbel (1959) was widely used (cf. Corbel 1964, 1971; Corbel & al. 1965; Gams 1966; Groom & Williams 1965; Muxart & al. 1965;

Pitty 1968; Pulina 1966, 1968; Markowicz-Łohinowicz 1968; Kotarba 1971; Chikishev 1972a, b; Gvozdetsky 1972; Markowicz & *al.* 1972). This enable the comparison of data obtained with similar initial assumptions.

J. Corbel (1959; *cf.* also Corbel & *al.* 1965; Corbel 1964, 1971) has given the following empiric formula for determining the denudation of limestone regions:

$$X = \frac{4ET}{100} \text{ m}^3/\text{km}^2/\text{yr} \text{ or mm}/1000 \text{ yr}$$

where E — is the mean annual effective outflow (in dm)
 T — the content of dissolved salts in water (in mg/dm³).

The significant differences are a result of the acceptance of the evaporation values by calculating the E parameter according to the formula $E = P - D$, where P is the mean annual precipitation in decimeters, D is the annual evaporation in decimeters.

J. Corbel (1959) used the theoretically calculated values of potential evaporation (on the basis of the mean annual temperature), hence with respect to arid areas the index values were distinctly lowered (*cf.* Pulina 1968, Markowicz & *al.* 1972). If meteorological data determining the field evaporation or individual runoff in a given area are available, the results will be more adequate.

We feel sure that, when computing the chemical denudation index, along with the value of the carbonate denudation index (X_C , calculated on the concentration of the HCO_3^- ions) the value should also be given of the total karst denudation index (X_K , calculated on the total mineralization — *cf.* Table 1). A comparison of the denudation of various karst formations — but exceptionally built of pure limestones — is possible only if both the above indices are available. The use of Corbel's formula allows to calculate the comparable values defining the rate of denudation, as surface lowering of the soluble rocks in mm/1000 yr or m³/km²/yr, also in mm/yr of the conventional soluble rock. This value should not be regarded as an absolute measure of denudation, but as an index useful in making comparison and permitting approximately to determine the effects of karst denudation.

It should be stressed that the calculation of the karst denudation index with an exactitude of 0.1 mm/1000 yrs, as is currently practised, is scientifically meaningless. In most publications containing calculations of the denudation index, no estimate of the error of the method is given. There is no need to explain that the results thus stated are deteriorated by error resulting from errors in all the assumptions and measurements used in computing the parameters in the formula. On the basis of many years observations of the same karst sources in the vicinity of Częstochowa (*cf.* Markowicz-Łohinowicz 1968, 1973), an attempt has been

made here to estimate the error. It has revealed that calculations carried out on the same assumptions of Corbel's method (taking into account field evaporation) are encumbered with the error of c. 10%, while, taking into account a modification of the method (Groom & Williams 1965, Pulina 1966) the error was in extremal case reaches 50%. Hence, it may be concluded that under favorable conditions (available mean data collected over a number of years on precipitation, field evaporation and variability range of the chemical composition of water), the karst denudation index is burdened to an error reaching 20%. If these data are not available and if denudation is determined on single analyses, on potential evaporation etc., the error of this method may even exceed 50%.

But even the magnitude of the error of this method does not cancel the geomorphological significance of the index of chemical karst denudation, because its values, calculated under various climatic and geologic conditions, differ by several orders of magnitude and agree with geomorphological observations. However, the geomorphological significance is indicated only by the magnitude order of the index and not by its absolute value in each single calculation.

It should be stressed that data obtained by investigating waters from springs of the exsurgence type have a far greater geomorphological value, both indrawing conclusions concerning climatic influence (cf. Harmon & *al.* 1972) and the effects of lithology on karst denudation as compared with data obtained from studies of river water. Data on waters from springs of the resurgence type are of intermediate value.

Chemical denudation

Within the area under consideration, there occur on the surface, under similar climatic conditions, formations of carbonate rocks, differing in age and lithology and forming isolated hydrogeological units. Hence, on the basis of the obtained results of chemical analyses it is possible to determine the intensity of chemical denudation of the particular lithostratigraphic formations.

The denudation index has been established after Corbel's formula (Corbel & *al.* 1965); the value of E was calculated on data cited by Schmuck (1969): for investigated area the mean annual precipitation is 600—700 mm/yr (average 650 mm/yr was used); the mean field evaporation 400—500 mm/yr (average 450 mm/yr was used) what makes $E = 2$ dm/yr.

The T value was accepted on results of chemical analyses: the carbonate hardness, expressed in mg/l CaCO_3 , to determine the carbonate denudation, and the mean total mineralization, expressed in mg/l of the dissolved salts, to determine the total karst denudation.

The effect of pollution is considerably smaller in the spring water than in the case of surface water, *e.g.* of river water. The percent content of constituents derived from pollution of rain water in the mineralization of ground waters in the investigated area the most probably does not exceed the salt content in water displaying the minimum mineralization (*cf.* spring No. 6 from Bunter deposits), that is 50 mg/l. The analyses of the salts content in rain waters sampled at Chęciny due to pollution gave a similar value up to 50 mg/l. The latter value corresponds to the rate of denudation of the order of 4 mm/1000 yrs. The denudation indices determined for the other formations ought to be reduced by the latter value. This would not, however, change the magnitude order of the calculated indices nor their mutual relations.

The denudation index values determined for the particular carbonate formations of the SW part of the Holy Cross Mts are shown in Table 1. The total karst denudation index attains values up to 70—147 mm/1000 yr in the case of waters from the Devonian dolostones, as compared with 19—31 mm/1000 yr in the case of waters from other soluble formations. Therefore here the denudation of dolostones is 3.5—5 times as great as that of limestones. A comparison of carbonate denudation indices likewise shows a value of 36—46 mm/1000 yr for dolostones and 10—23 mm/1000 yr for limestones, the denudation of dolostones being thus 2—3 times that of limestones. Regarding similar climatic, probably also soil conditions in the outcrops of carbonate rocks affecting the biogenic CO₂ production, so important an increase in the carbonate capacity of karst waters may be explained only by "the salt effect" since it is known that other salts admixture considerably increases the solubility of carbonates (*cf.* Shternina & Frolova 1952; Roques 1964, p. 342).

The chemical denudation of dolostones being several times as strong as that of limestones explains the phenomenon observed within the investigated area that dolostones outcrops form lower gently sloping elevations or depressions in relation to the neighboring limestones. This conclusion agrees with the suggestions of Douglas (1964, 1965) postulating that under determined conditions the dolostones are less resistant to karst denudation than limestones (*cf.* also Ek & Roques 1972) while it contradicts the current view suggesting always greater resistance of dolostones to karst denudation.

FINAL REMARKS

The authors' investigations revealed a strong differentiation of the chemical composition of karst waters within the area under consideration dependent on the lithology of soluble formations as well as on the annual seasons (*cf.* Harmon & *al.* 1972).

The most distinct differences are in the waters from Devonian dolostones which display a high Cl^- and SO_4^{2-} ion content. This is caused by a primary admixture of chloride and sulfate minerals in the dolomite sequence.

A strong differentiation in chemical denudation has been reported, and it was demonstrated, that it is much greater in the Devonian dolostones than in limestones of various age. This explains why, in relation to dolostones, the limestones are the range-building rocks in the Holy Cross Mts. This phenomenon is most likely a general law, also stated in the Western Tatras (cf. Fig. 1), where the most characteristic feature of the Middle Triassic carbonates are the limestone ridges paralleling the passes developed along the dolomite interbeddings.

The strong differentiation of chemical denudation dependent on the lithology of carbonate rocks shows the importance of Corbel's (1959) chemical denudation index with regard to geomorphological speculations under undifferentiated climatic conditions. In view of the lithological differences not only Ca^{2+} but the sum of ions, too, should be taken into account in calculating the above index. On the other hand, in view of the seasonal differences in denudation, the most frequent or mean mineralization should be determined on the basis of repeated measurements taken at various seasons (cf. Douglas 1965). Since the karst denudation index thus determined is usually affected by an error of at least 20%, thus the magnitude order of this index, and not its absolute values, is of the geomorphological importance.

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**ZALEŻNOŚĆ DENUDACJI KRASOWEJ OD BUDOWY GEOLOGICZNEJ
NA PRZYKŁADZIE POŁUDNIOWO-ZACHODNIEJ CZĘŚCI
GÓR ŚWIĘTOKRZYSKICH**

(Streszczenie)

Południowo-zachodnia część Gór Świętokrzyskich w okolicach Chęcina jest wyjątkowo dobrym poligonem, na którym można rozwiązywać (por. fig. 1—3) zagadnienia zależności chemizmu wód krasowych i denudacji chemicznej od budowy geologicznej (por. Głazek & Markowicz-Łohinowicz 1973). Na podstawie analiz chemicznych wód krasowych, wykonanych w różnych porach roku (tab. 1), zarejestrowano sezonowe zmiany ich chemizmu (fig. 5), obliczono wskaźniki denudacji chemicznej i wykazano zależność składu tych wód od litologii danej formacji krasowiejącej (fig. 6). Wykazano, że denudacja dolomitów dewońskich jest kilkakrotnie większa od denudacji dewońskich i triasowych wapieni. Wysoka zawartość jonów SO_4^{2-} i Cl^- w wodach z dolomitów dewońskich wskazuje na hipersalinarne warunki ich sedymentacji. W pracy ponadto porównano zakresy sezonowej zmienności wód krasowych badanego regionu oraz części obszaru Jury Polskiej (fig. 4 i 5), a także omówiono metodę obliczania (por. Corbel 1959) wskaźnika denudacji krasowej, błędy jakimi obarczone są takie obliczenia oraz geomorfologiczne znaczenie tego wskaźnika.

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