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The discharge-quality relationship interpreted for karst springs by a new karst model

G. IZÁPY & L. MAUCHA

Abstract
Experiments carried out in Hungary have implied that the karst mechanism which controls the variation m spring discharge during depletion also applies to changes in some quality components in the spring water.
The earlier studies by CSER and MAUCHA in Hungary have demonstrated the depletion discharge turne series to describe in a logarithmic plot a five-sided polygon. The phenomenon is attributable to the successive depletion of five duct systems having different cross sectional areas at significantly different rates. The flow in the wider ducts causes backup in the narrower laterals and thus prevents the latter from becoming depleted, with the consequence that for a few days at times of flood, radical changes may take place in the composition of the spring discharge.
Taking also into consideration the circumstance that from the waters seeping at slower rates more carbonates are likely to precipitate in die cave (the water becoming softer in the process), the more highly concentrated (harder) directly infiltrating high flows in the cave may produce higher concentrations in the spring discharge by blocking temporarily the softer waters in the lacerai. passages. It is true if the waters don't originate from sinkholes.
In limestone areas, if the seepage waters depleting at a slower rate originate from limestone, an increase in the Ca- and $11CO_3$-ion contents is alone observable. However, if these waters originate from both limestone and dolomitic rocks, then the concentration of the Mg-ions will also decrease in the composition of die high spring discharges.
Observation data have fully corroborated die described mechanism.

Résumé
Puisque le drainage souterrain se fait dans des fractures de dimensions diverses, lorsque l'eau se fait rare, elle disparaît de ces fractures à des moments qui peuvent différer de quelques jours à plusieurs semaines. Ce mécanisme karstique explique aussi que les eaux qui s'infiltrent plus lentement deviennent plus douces, parce que leurs carbonates précipitent plus facilement dans la grotte. Les eaux plus dures sont celles qui coulent plus vite, et elles rendent la résurgence plus chargée en carbonates tant qu'elles bloquent les eaux plus douces dans les passages latéraux étroits.

L PROBLEM FORMULATION

In 1954 two conflicting phenomena were registered in the karstified Aggtelek region in Hungary. KESSLER (1955) has found the hardness of the sink-fed Jósva spring to decrease at times of floods. In the same year JAKUCS (1955) demonstrated that the Ca-ion content in the yield of the likewise sink-fed Komlôs spring increased during floods. In 1983, we have concluded from a study on eight major karstic springs in the same area, at the Karst Research Station Jósvafó of VITUKI, that the decrease in hardness in the discharge of sink-fed springs occurred at short interruptions on the rising limb of the flood hydrograph and that the increase of the Ca-ion content was observable during floods at all springs invariably, but that this was accompanied in the springs with partly dolomitic catchments by a decrease in the Mg-ion concentration (Fig. 1). An attempt is presented here at interpreting this phenomenon, since no satisfactory explanation could be found in the international literature.

II. DEPLETION STUDY ON THE SPRINGS

Using the observation data of 1970, CSER (1978) has demonstrated that the depletion curve plotted to logarithmic scale of the discharge Lime series of the Nagy-Tohonya spring can be described by a five-sided polygon. This phenomenon could be detected in all

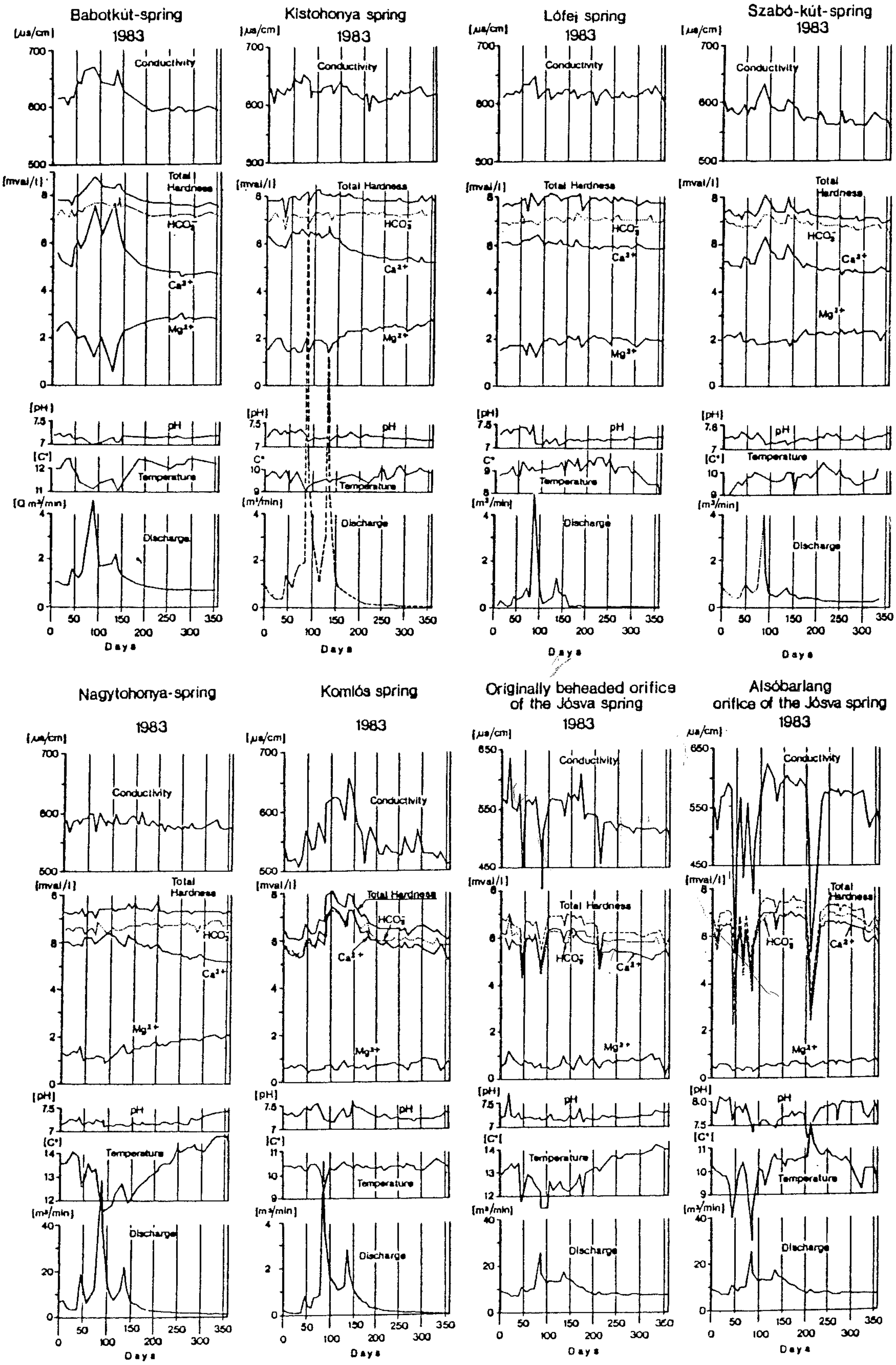

Figure 1: Conductivity, hardness, pH, temperature and discharge of 8 springs (1983).

springs emerging in the karstified region composed of Middle-Triassic limestones and dolomites. It became clear therefrom that the earlier assumption of a double porosity in the karst provides only a crude approximation to the hydraulic behaviour of these aquifers. More accurate observations revealed that the five-sided discharge depletion time series corresponds to functions of the foret :

$$Q = Q_o \cdot e^{-kt}$$

with five different time constants k, which describe successive, mutually exclusive depletion of five reservoirs consisting of ducts having different cross sectional areas. This means actually that the karstified rock includes five-fold porosities (Fig. 2). This represents five cold (and if there is a deep karst) one warm discharge components; in other words the discharge of karst springs comprises waters of six different ages.

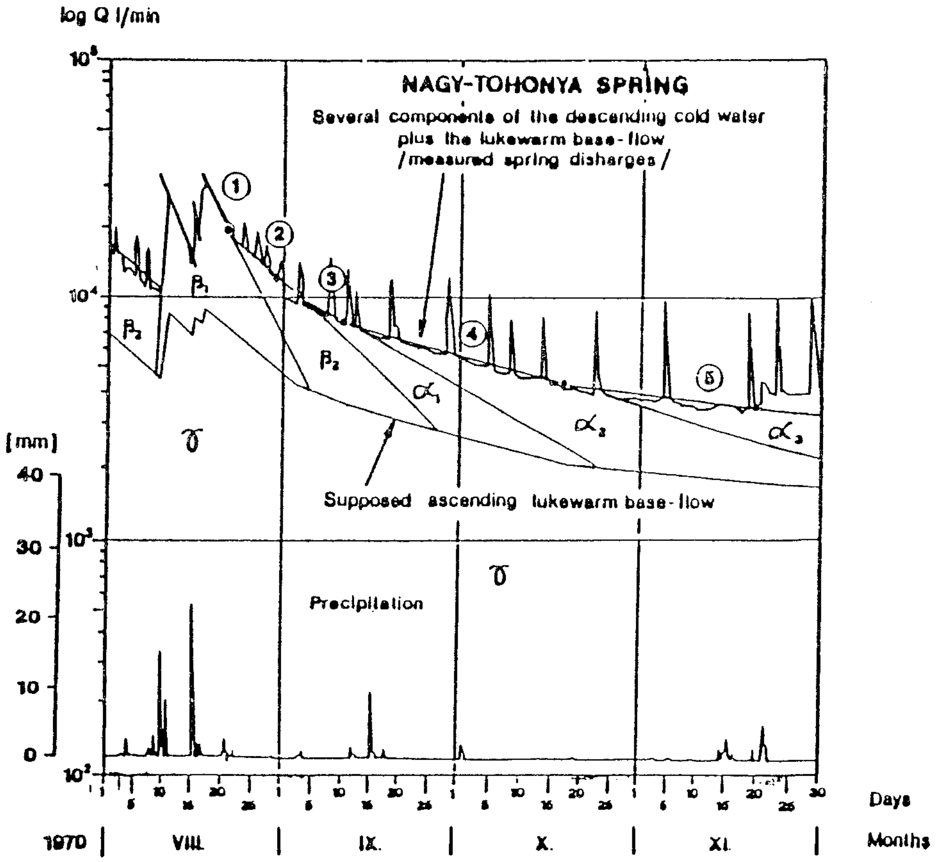

Figure 2: Nagy-Tohonya spring. Several components of the descending cold water plus the lukewarm base-flow. Measured spring discharges.

III. NEW KARST MODEL FOR INTERPRETING DEPLETION BEHAVIOUR

An interpretation of the phenomenon observed has been derived by MAUCHA (1989), starting from the tectonics of the karstified rocks. A typical feature of the Triassic karsts in Hungary is that the rock mass is dissected into statistically 50 by 50 metre large blocks bounded by closely vertical fracture lines. This network of fractures is termed the main fracture system, while the enclosed blocks are called elementary blocks. If it is assumed that two kinds of fractures developed in the interior of the elementary blocks, the wider secondary fractures and the narrower microfissuration, we have already three storage spaces depleting at three different rates. Since the main fractures widen in the principal drainage directions into tunnel-like passages (the main and lateral branches of underground streams), we arrive at the five storage spaces assumed, which deplete independently from each other in some periods.

The karst model constructed in accordance with the foregoing is illustrated in Fig. 3 and reveals that the

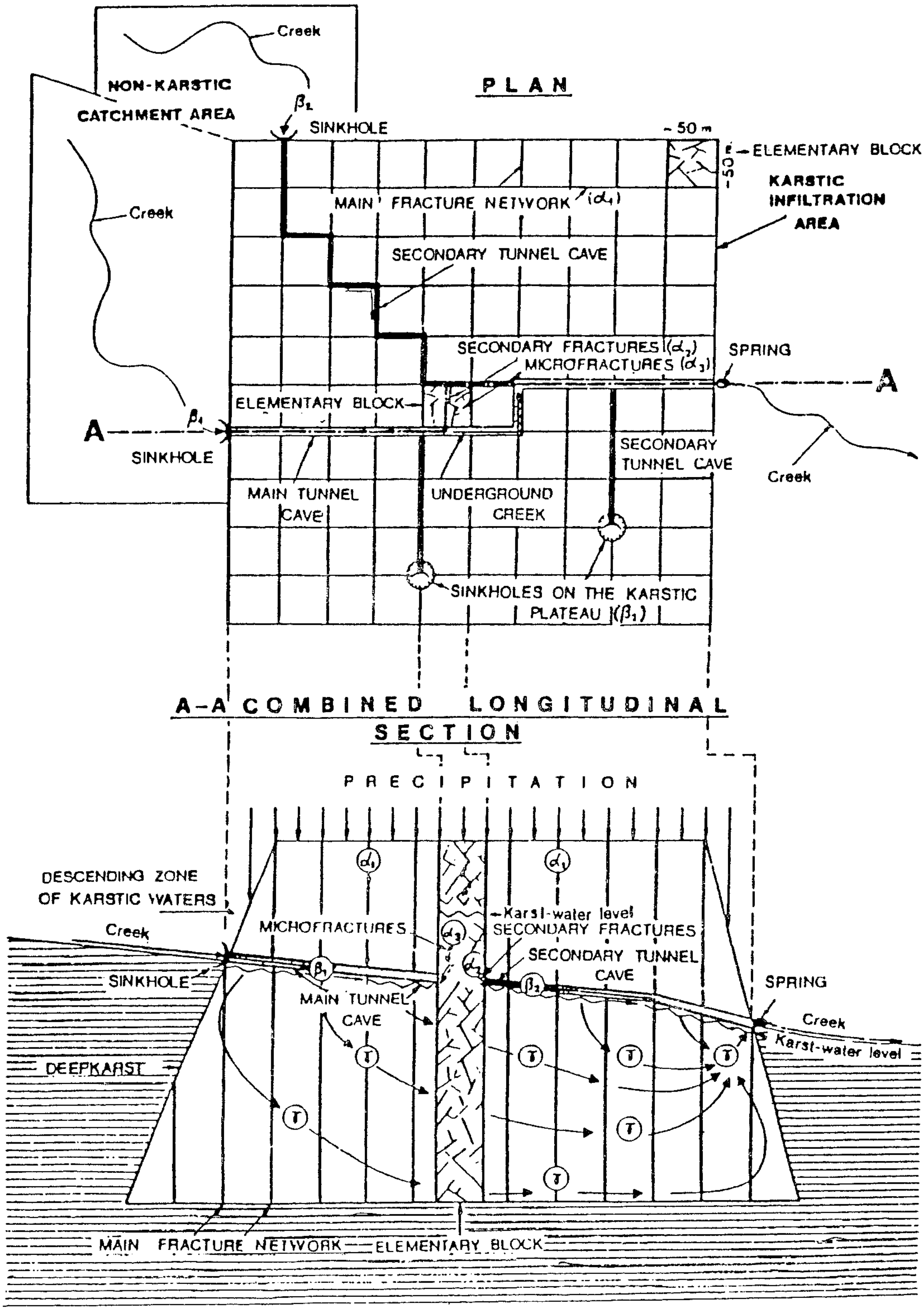

Figure 3 : New karst model.

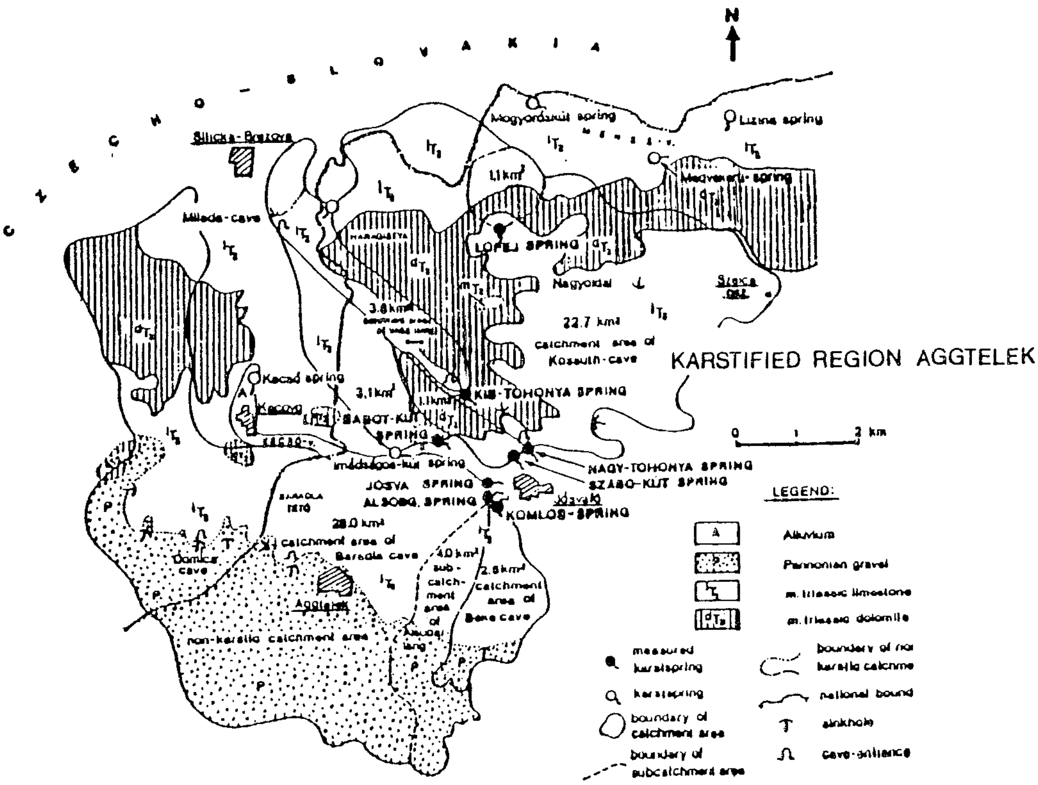

Figure 4: Karstified region Aggtelek.

successively decreasing passage width results in five successive depletion processes, sine the flow phenomena known from surface streams apply also to the underground ducts. Full flow in those having larger cross sections prevents, by the backwater created, all smaller lateral streams from becoming depleted. These periods of exclusion may fast from a few days to several weeks. Our investigations have implied that 80 % of the infiltrating precipitation arrive at the spring through the main fracture system, while 20 % by flow along the surface of the blocks. In dolomites the infiltration process is a reversed one, in that fracturing of the elementary blocks is about four times as high as in limestones and accordingly these convey 80 % of the infiltration, leaving only 20 % for the main fractures. This is concluded from the fact that, in the main fracture system in limestones, the fluctuation of the karst water table is about four times as wide as in dolomites (20 and 4 m, respectively).

IV. HYDROCHEMISTRY OF THE SPRING WATERS

The general map and the geological environnent of the eight studied springs are shown in Fig. 4.

The time sertes of discharge, temperature and chemical components for the year 1983 are shown in Fig. 1. Out of the chemical components, six were determined, i.e., electrical conductivity, total hardness, hydrogencarbonate-ion, Ca- and Mg-ion and the pH. The first value is presented in μS/cm units, while the others, except for the pH, in mval/L.

In Table 1 the measurement data are presented together with the size of the catchment area of each spring studied, the surface ratio of limestone to dolomite in them, further the mean and extreme values of the spring discharges and water temperatures in the year 1983.

V. THE DISCHARGE-QUALITY RELATIONSHIP

The analytical data have revealed (Fig. 1) that in periods of rising discharges the Ca-ion concentration increased in ail the springs studied. In springs draining purely limestone catchments, this effect is more pronounced and is accompanied by strong simultaneous increases in electric conductivity, total hardness and hydrogencarbonate ion. The average

Springs	Catchment			Spring yield				Water temperature		Mean water chemical composition								
	area	limestone dolomite	ratio of stone areas	mean	max. min.	change		mean	max min	pH	conduc-tivity	total hardness	Ca^{2+}	Mg^{2+}	$q^{Ca,Mg}$	HCO_3^-	NO_3^-	k^h
	km^2		limestone / dolomite	l / min		Q_{max}/Q_{min}	$Q_{max}/Q_{átl}$	°C			μScm^{-1}	mg / l mval/l			Ca eé mg/l / Mg eé mval/l		mg/l	total hardness / bicarbonate hardness
Babot-kút	3.1	2.8 0.3	9.3	1340.	4580. 720.	7.	3.	11.9	12.4 11.0	7.1	619.	221. 7.9	111. 5.6	26. 2.3	2.4	449. 7.4	2.2	1.07
Kis-Tahonya	3.6	2.2 1.4	1.6	1022.	17890. 28.	639.	18.	9.7	10.2 9.0	7.2	622.	221. 7,9	117. 5.8	25. 2.0	2.9	437. 7.2	2.6	1.10
Lófej	1.3	0.9 0.4	2.3	480.	6580. 20.	329.	14.	9.0	9.6 3.1	7.2	617.	219. 7.8	120. 6.0	22. 1.8	3.3	429. 7.0	0.9	1.11
Szabó-kút	1.3	0.5 0.8	0.6	460.	3000. 250.	12.	7.	9.7	10.4 9.0	7.2	583.	205. 7.3	105. 5.2	26. 2.1	2.5	416. 6.8	7.6	1.07
Nagy-Tahonya	22.7	15.9 6.8	2.3	6470.	61650. 1580.	39.	10.	13.3	14.8 11.5	7.2	503.	204. 7.3	116. 5.8	18. 1.5	3.9	404. 6.6	3.2	1.10
Komlós	2.6	2.5 0.1 (1)	25.0	841.	17100. 50.	342.	20.	10.3	10.7 9.3	7.2	554.	108. 6.0	121. 6.1	8. 0.7	8.7	377. 6.2	2.4	1.09
Alsóbarlang orifice of the Jósva spring	4.0 (3)	3.8 0.2 (1)	19.0	1370. (2)	27400. (2) 100. (2)	270.	20.	10.1	12.1 7.0	7.7	544.	188. 6.7	122. 6.1	7. 0.6	10.2	377. 6.2	6.6	1.08
Originally beheaded orifice of the Jósva spring	28.0 (3)	24.4 3.6	6.0	8230. (2)	32600. (2) 6600. (2)	4.	5.	13.0	14.2 11.5	7.2	536.	178. 6.4	113. 5.7	9. 0.7	9.1	358. 5.9	11.5	1.09

(1) surface projection of the supposed subsurface dolomite strata
(2) divided values of the measured yield by estimation
(3) estimated catchment areas belonging to average yields

Table 1 : Quantitative and qualitative values of the Jósvafö karstsprings in 1983 year (in decreasing order of the total hardness).

amount of Mg-ion is one-half or one-third of that in dolomite springs and remains unchanged at times of flood. In contrast thereto, in springs draining partly dolomitic catchments, parallel to the increase in the Ca-ion the concentration of Mg-ion decreases like a mirror image, while the changes in conductivity, total hardness and hydrogencarbonate-ion content are less conspicuous, or hardly detectable at ail, as it is the case e. g. with the Nagy-Tohonya spring.

The results of the vigorous sink activity are clearly observable at the two emergences of the Jósva spring. Although the concentration of the components would be expected to increase during floods, actually rapid decreases occur as a consequence of the soft water entering through the sinks, as reflected by the sharp minima.

VI. EXPLANATION OF THE DISCHARGE-QUALITY RELATIONSHIP

In limestone catchments, the flood-time increases in conductivity, total hardness and Ca-ion content could be attributed solely to the fact that owing to slow depletion during low-water periods the $\alpha_{2,3}$ (Fig. 2, 3), originating from the fine fissures deposit stalactites and lime tufas along their path to the spring, so that their hardness decreases. At times of flood, however, the directly infiltrating α_1 waters are depleted at fast rates and there is no time available for carbonates to precipitate. For this reason, these waters are more concentrated than the $\alpha_{2,3}$ waters.

The foregoing precipitation effect is made more pronounced by the exclusion effect involved in the model, as a result of which the α_1 and $\alpha_{2,3}$ waters are prevented from mixing around the flood peak. On the other hand, the model offers the only explanation for the drop in the Mg-ion content, taking also into consideration the four-fold fracturing of the elementary dolomite blocks. Assuming that the elementary blocks of a particular spring consist of limestone and dolomite in equal proportions, then at times of low water, i.e., over the major part of the year, the base flow of the spring is contributed in the ratio 1:4 rather than 1:1 by the dolomite. This is why the components dissolved from the dolomite predominate in such periods.

In flood periods the flow of non-sink infiltration (α_1) starts increasing in proportion with the area and depletion of the elementary blocks is temporarily hindered. In this case, the spring discharge originates in 1:1 proportion from limestone and dolomite areas. The drop of the Mg-ion in springs draining in part dolomite catchments is attributable to the lower proportion of the dolomitic solution. These changes in chemistry are thus caused by hydraulic phenomena.

The fluctuations in conductivity, total hardness, hydrogencarbonate- and Ca-ion are narrower in catchments comprising minor parts of dolomite, rince no precipitation can occur in the dolomitic part. This is why the spring waters originating from these ones retain their original concentration at times of low flow. In the spring water mixed with the base flow from the limestone part of the catchment the resultant composition differs less, or but hardly from the concentration of the directly infiltrating, non-sink waters. The highly stable concentration e. g. of the Nagy-Tohonya spring is explained thereby.

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Adresse des auteurs:

G. Izapy & L. Maucha
Szigeti Jozsef u. 7 1/5
H-1041 BUDAPEST
HONGRIE