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KARST WATER RESOURCES RESEARCH IN HUNGARY AND ITS SIGNIFICANCE

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1. Importance of karst water resources

Karst water is of great practical importance in Hungary. Cold and thermal springs, the water of spas and mineral-medicinal waters are all to a considerable extent of karstic origin. The activity of these groundwater systems has resulted in the formation of many caves of cold or thermal-water origin.

Hungary is located in the central, subsiding part of the Carpathian Basin; thus, heatflux here is higher than the average elsewhere in the world. Under most of the mountain areas of the country there are carbonate rocks of the Palaeozoic (Devonian and Carboniferous), or Mesozoic (mainly Middle and Upper Triassic — but also lesser areas of Jurassic and Cretaceous) and Cainozoic (i.e. Eocene, Miocene, Pliocene). In sum, almost one fourth of the basement formations are karstic, totalling 25,000 km^2 *(Fig. 1)*. These carbonate formations are from nine different geological epochs.

Within the near-surface karstic areas of the country a total of 2,700 km^2 of so-called "unconfined" karst highlands are known. They include ca 1,800 km^2 of exposed recharge or direct infiltration area. The remainder of the karstic areas are covered by thick Cainozoic sediments and function as deep-karst aquifers under pressure (artesian conditions). Karst aquifers that are deeply subsided and several thousand metres thick locally, originally recharged many natural karst springs. Some of these have already dried out as a result of human influence, but there are still several thermal and medicinal springs active in Hungary today.

Karst areas that are unconfined or partly covered by younger rocks (Jurassic, Cretaceous, Eocene, Miocene, Pliocene or Pleistocene) still feed springs whose water can be obtained by gravity or by pumps to serve local domestic water-supply systems. These waters are of excellent quality. In the karst areas the proportion of mean annual precipitation that infiltrates and provides water suitable for drinking is much greater than surface runoff will yield in equally mountainous but non-karstic parts of the country. This phenomenon can be explained by the fact that in karst terrains precipitation in-

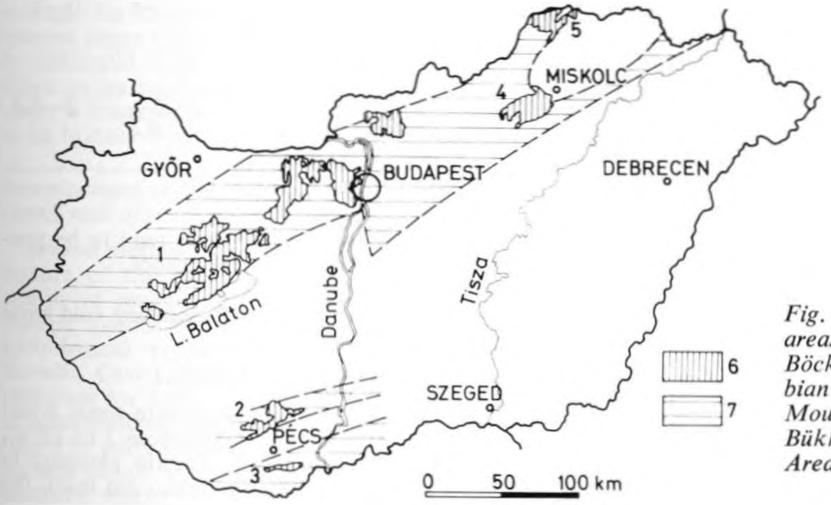


Fig. 1. Surface and covered karst areas of Hungary (after T. Böcker). Legends: 1. Transdanubian Mountain Ranges, 2. Mecsek Mountains, 3. Villány Hills, 4. Bükk Mountains, 5. Gömör Karst Area, 6. Outcropping karstic rocks, 7. Covered karst

Table I.

Karst areas of Hungary characteristic extreme values of all water types in the water budget

Type of water	*pH*	*Electric conductivity $\mu s\ cm^{-1}$*	*Total hardness nk°*	Ca^{++}	Mg^{++}	HCO_3^-	Cl^- *mg/l*	SO_4^-	NO_3^-	NH_4^+
Precipitation	4—8	10—670	0.1—10	1—50	0.1—15	6—100	0.2—24	0—150	0.5—50	0.2—16
Surface runoff at the karst-lysimeter	7—8	25—200	2—3	10—70	4—7	6—10	5—2	2—30	2—10	1—3
Surface runoff at the swallow-holes	6—8	60—670	1—6.5	8—50	1—9	1—100	1—24	6—150	1—190	0.1—16
Subsurface runoff in soil	8—10	200—1.600	1—20	8—30	1—10	130—470	0.3—4	4—40	0.5—50	0.1—1
Infiltration in karstic rock	8—9	130—780	3—25	15—100	4—50	70—620	0.3—2	8—50	0.2—40	0.1—1
Dripping waters in caves	7.5—7.8	620—790	14—25	90—160	0.5—19	200—480	3—30	25—60	0.5—90	0—0.8
Waters of cave streams	7—8	150—850	3—27	18—140	2—16	60—430	6—105	6—125	6—40	0—2
Waters of cold springs	6.7—8.1	340—860	5—27	30—220	0.7—37	85—490	1.7—40	6—150	0.8—50	0—0.9
Waters of thermal springs	6.5—7.8	480—900	16—27	76—125	29—54	360—510	20—45	10—110	0—6	0—1
Waters of thermal wells	6.7—7.0	850—1,200	27—40	90—250	25—70	490—800	90—150	100—290	0—0.4	0—1.2

filtrates rapidly and, once underground, it is less subject to evaporation. In the most extensive mountains, the Transdanubian Ranges, because of coal- and bauxite-mining, "active": karst water protection has become a necessity. Water pumped from the mines has recently surpassed the natural recharge (460 m^3/min.). The operation of deep mines, the environmental impact studies for dewatering of mines and the need for domestic water supplies have resulted in the multipurpose development of the theory and practice of karst hydrology. The costs of specific hydrogeological projects tend to be proportional to their economic significance.

2. Results of investigations of descending cold karst water resources

Characteristic precipitation conditions

Hungary is located in the temperate zone. Average annual air temperature ranges from 7 to 12° C. The average elevation of the karstic plateaus in Hungary is about 500 m above mean sea level, the

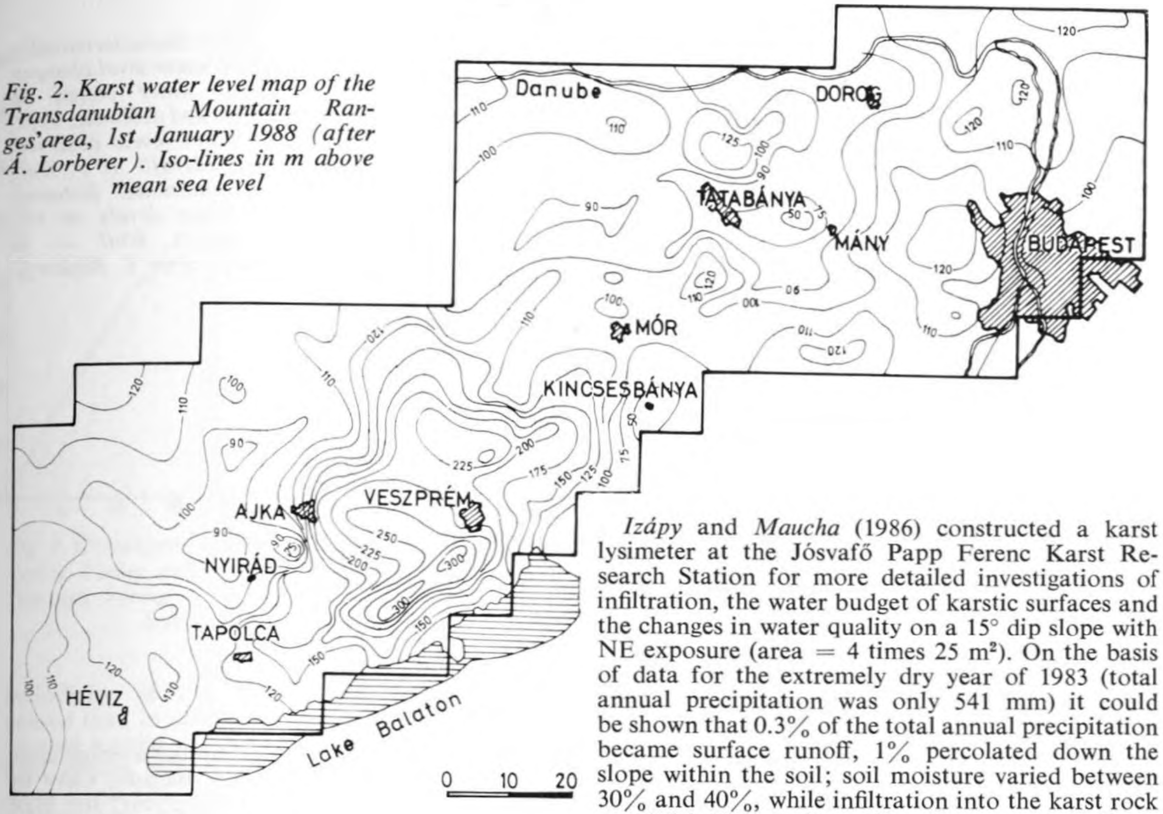


Fig. 2. Karst water level map of the Transdanubian Mountain Ranges'area, 1st January 1988 (after Á. Lorberer). Iso-lines in m above mean sea level

highest being in the Bükk Mountains (900 m amsl) and the lowest in the Villány Mountains (350 m amsl). The mean annual precipitation ranges accordingly from 500 to 900 mm; it increases with elevation and towards the West.

The chemical composition of rainwaters was studied in detail by *Izápy* and *Maucha* (1987) in three karst regions. Characteristic results are presented in *Table 1.* It is a remarkable feature that in forested areas under natural conditions the ammonia ion concentration in rainwater is double the average for the country. The reason this is the intense degradation of forest soils (2 to 4 mg/l). In industrial areas and the surroundings of large cities on the contrary, the ammonia content of rain water is lower, while Ca and Mg ion contents prove to be higher.

Investigations of the infiltration and the subsurface runoff rate of precipitation

Several attempts have been made to form a clear picture of the changes of the water budget and quality of precipitation water as it enters the karst masses. *Kessler* (1954) was the first to investigate the hydrological properties of the swallow holes of Baradla Cave. *Böcker* (1986) showed from runoff plot data for 1978 to 82 (five year interval) that on a grass-covered slope on dolomite near Jósvafő (dip 15°, with an area of 1,834 m^2) the amount of surface runoff was only 2% of the mean precipitation of 5 years.

Izápy and *Maucha* (1986) constructed a karst lysimeter at the Jósvafő Papp Ferenc Karst Research Station for more detailed investigations of infiltration, the water budget of karstic surfaces and the changes in water quality on a 15° dip slope with NE exposure (area = 4 times 25 m^2). On the basis of data for the extremely dry year of 1983 (total annual precipitation was only 541 mm) it could be shown that 0.3% of the total annual precipitation became surface runoff, 1% percolated down the slope within the soil; soil moisture varied between 30% and 40%, while infiltration into the karst rock was 12%. Changes in quality of the water are shown in *Table 1.* It is clearly seen that the pH of the precipitation increases by about 2.0 after percolating through the thin (30 cm) soil layer and its hardness grows threefold in these slightly basic soils. On the other hand, nitrogen contamination drops to one fourth or one sixth of that in the rain. *Zámbó's* (1986) investigations added new date to the lysimeter measurements because he studied in detail the changes — over time and space — of the CO_2 content of rain water filtering into doline fills. Amongst other results he claimed that the dissolved CO_2 content and aggressivity of the ground water rises in proportion to the increase of soil thickness.

Investigations of the water quality in Baradla Cave showed that surface runoff can be enormously contaminated because of improper use of chemicals over neighbouring agricultural areas. This is indicated by the extremely high ammonia and nitrate content of waters running into karst swallow holes.

Hydrology of cave waters

The water infiltrating below the surface will appear on the ceilings of caves in the form of dripping water. The amount and quality of such waters has been studied in Vass Imre Cave in Jósvafő, Szent István Cave and Létrási-vizes Cave in the Bükk Mountains, in the thermal water caves of Budapest and Alba Regia Cave in the Bakony Mountains. *Gádoros* (1961), *Czájlik* and *Fejérdy* (1960—61), *Böcker* (1975), *Lénárt* (1978), *Zentay* (1986) and *Takácsné Bolner* (1987) have all made important studies in this field. According to *Izápy*

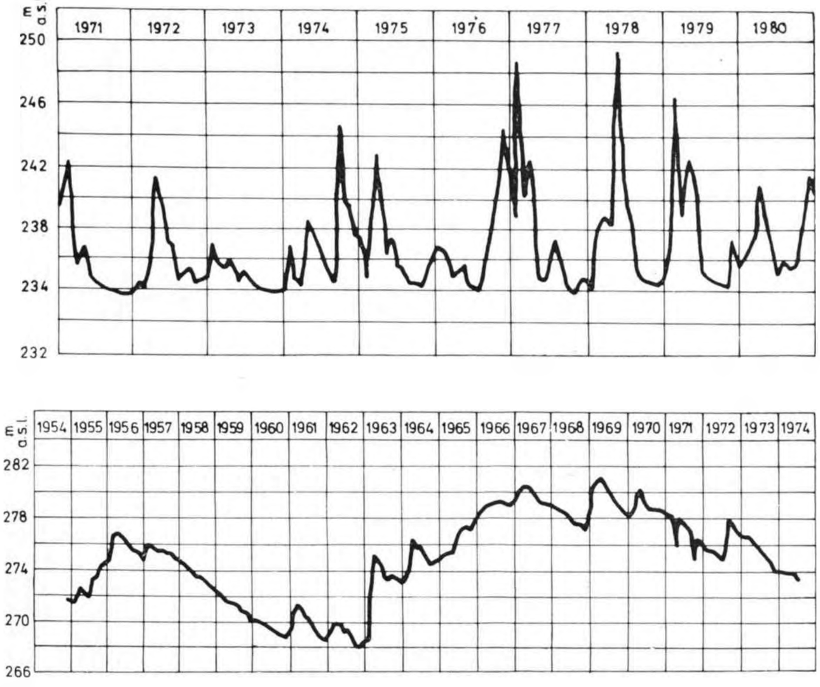


Fig. 3. The characteristically differing water level changes of karst water stored in limestone and dolomite. Top: Karst water levels observed in the Jósvafő N°1 Well — in limestone. Bottom: Karst water levels in the Nemesvámos Well — in dolomite (after T. Böcker)

and *Maucha* (1980) the yield of drip sites ranges from 0 to 7 l/day; at seven stations in Vass Imre Cave the annual average was 230 l/year. Kessler, Böcker, Lénárt and Maucha also used the data for infiltration calculations and for estimating vertical filtration velocity. The average catchment area of a drip measurement site in Vass Imre Cave is 1.3 m^2 according to the water budget investigations in the Jósvafő area, based on specific yield. Over a ten year study period mean annual precipitation was 666 mm and the mean yield for a 1 m^2 area was 177 l/year, a value which is 27% of the total (mean) precipitation.

The quality of dripping waters was first analyzed by *Maucha* (1929) in Baradla Cave, and again by *Czájlik* and *Fejérdy* (1959). On the basis of the study of 50 drip sites it can be stated that waters from within stalactites have an average hardness of 25° (Germ.) while waters outside have only 15° (Germ.) The hardness of dripping waters is maximum during the vegetation growth period and drops to a minimum in winter — because soil plays a decisive role in the karstification processes. Later, systematic investigations proved that the chemical composition of drip waters is very similar to that of local spring waters, but the concentrations of individaul constituents are more constant. Water quality changes are primarily indicating the increase of environmental contamination in the study area. Recently *Jakucs* and *Kevei* (1986) have made a number of drip water analyses in order to discover whether there is dripstone degradation, as they had assumed.

Quantitative and qualitative investigations of streams in caves were begun by *Kessler* (1954) in Baradla Cave; later, *Czájlik* and *Fejérdy* (1960) carried on the work in Béke Cave. Our most recent investigations showed that the annual average contaminant transport flux through Baradla Cave in the period, 1982 to 87, was 115 kg/year; the Styx stream (from the Domica-section in Czechoslovakia) supplies 17% of the total. *Gádoros* (1966) showed that in Kossuth Cave pressure-waves pass through at 1,000 m/hour and a wave of indicator dye at appr. 100 m/hour. Extreme values of our analyses are displayed in *Table 1.*

Karst water level studies

Beginning 1954 in the Transdanubian Mountain Range at the initiative of Kessler, karst water observation wells were drilled to collect data on changes of water levels. *Fig. 2* shows that on the basis of the data from about 150 observation wells a map can be constructed annually to display the karst water levels on the Transdanubian Mts. It has become possible to monitor human impact. Of great importance are the first, experimental, maps of karst water levels by *Szádeczky* (1948) and *Mike* (1963), and afterwards the wellconstruction activities of *Sárváry*, *Müller* and *Böcker* (1965—76) and *Lorberer* (1977—88) which are summarized in the annual karst water level maps. The systematic observation of changes of stored water resources by *Lorberer* has extended the area depicted in the karst water maps beyond the unconfined into the confined zones, by calculating the different levels according to pressure gradients.

The multi-annual record of karst water level changes shows that, in response to precipitation, in limestone aquifers the water level returns every year to an almost identical base level while in dolomitic aquifers water levels follow the multi-year

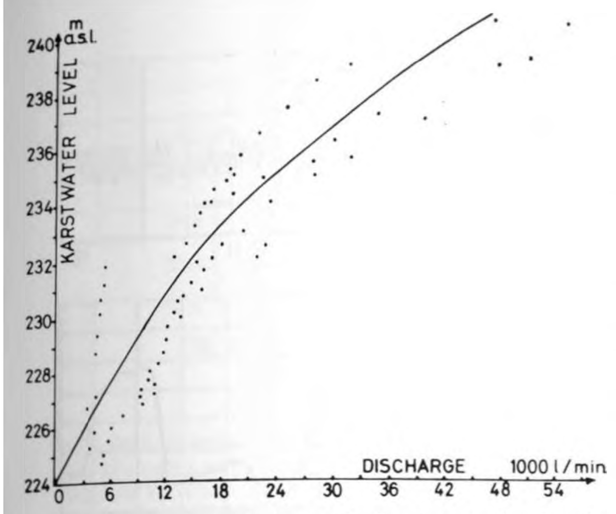


Fig. 4. Correlation between the karst water level in the Szelce Valley well and the discharges of the Nagy Tohonya Spring — in a period of increasing water level (daily data of 1977)

periodicity of the precipitation. *Gerber* (1965) proved that, in observation wells drilled into partly covered karstic aquifers, atmospheric pressure and tidal effects will also influence the behaviour of water levels *(Fig. 3)*.

From data on level changes in the Nagy-Tohonya spring catchment ("Szelce-völgy drilled well") *Maucha* showed that spring discharges correlated with increasing water levels. He stated that changes of the karst water level (H) are proportional to the three-fourth power of the spring discharge (Q).

$\triangle H = n.Q^{3/4}$ [m]

The changes are governed by the above relationship *(Fig. 4)*, in which $\triangle H = H—H_{min}$: n = a physical constant whose value approximates 1, and dimension is [min/m^2] if the dimension of Q is [m^3/min].

Comprehensive research on springs

Papp (1940—50), *Kessler* (1952—65), *Szabó Pál* (1953), *Rádai* (1954—88), *Jakucs* (1960), *Venkovits* (1960), *Balázs* (1954—64), *Böcker, Müller* and *Sárváry* (1965—75), *Hazslinszky* (1964), *Gádoros* (1971), *Aujeszky* and *Scheuer* (1972), *Juhász* (1973), *Tóth* (1973), *Rónaki* (1975), *Szalontay* (1965—75), *Dénes* and *Deák* (1977), *Lénárt* (1977), *Lorberer* (1975—88) and *Sásdi* and *Szilágyi* (1985) have pusblihed spring and water quality research works of fundamental importance in the exploration of the karstic springs of Hungary.

Between 1952 and 1965 and within the framework of VITUKI, *Kessler* with the assistance of *Rádai*, developed a National Register of Springs of Hungary. This was further expanded by *Böcker, Müller* and *Sárváry* (1965—85). About 2000 springs were measured during 10 to 25 years of work.

During investigations of 15 large karst springs, 15 to 25 years of continuous instrumental recording have been obtained and a wealth of knowledge accumulated. The Lófej, Nagy-Tohonya, Kis-Tohonya and Vecsem Springs prove that at least the following factors have to be taken into account:

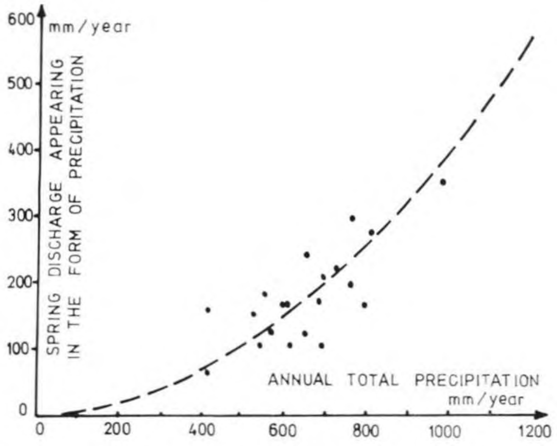


Fig. 5. Parabolic correlation of precipitation and discharge — Jósvafő Nagy Tohonya Spring — 1964 to 1983 years

The effect of precipitation

From 20 years of continous recording of precipitation and discharge at Nagy Tohonya Spring, *Maucha* (1988) stated that the correlation of total precipitation (C) and annual spring discharge (Q) is well defined by the parabolic function:

$Q = c^2/2{,}500$ [mm/year]

At the same time this correlation represents the relationship between annual infiltration and annual total precipitation by an approximate (not corrected) function *(Fig. 5)*.

Siphon effects at the springs

At both the Lófej and the Nagy Tohonya Springs karst siphons are able to produce non-climatic discharge fluctuations (outbursts) equal to several multiples of base flow. At Lófej Spring laboratory experiments and models indicate that two large siphons and one small siphon, connected in sequence and in parallel respectively, produce outbursts of 20 to 500 m^3 yield *(Maucha 1966)*. A 5,000 m^3 outburst at Nagy Tohonya Spring was first detected by *Kessler* (1965). This is produced by a side passage siphon because the discharge does not decrease between the outbursts. *Gádoros* (1966) showed that about 1.5 to 2.0 hours after each outburst there is slight increase of water temperature; it is concluded that the water recharging the main gallery is not as cold as the side passage stream feeding the siphon.

At Sárkány-kút Spring in the Mecsek Mountains *Rónaki* (1988) has observed a maximum of 21 siphon outbursts a day.

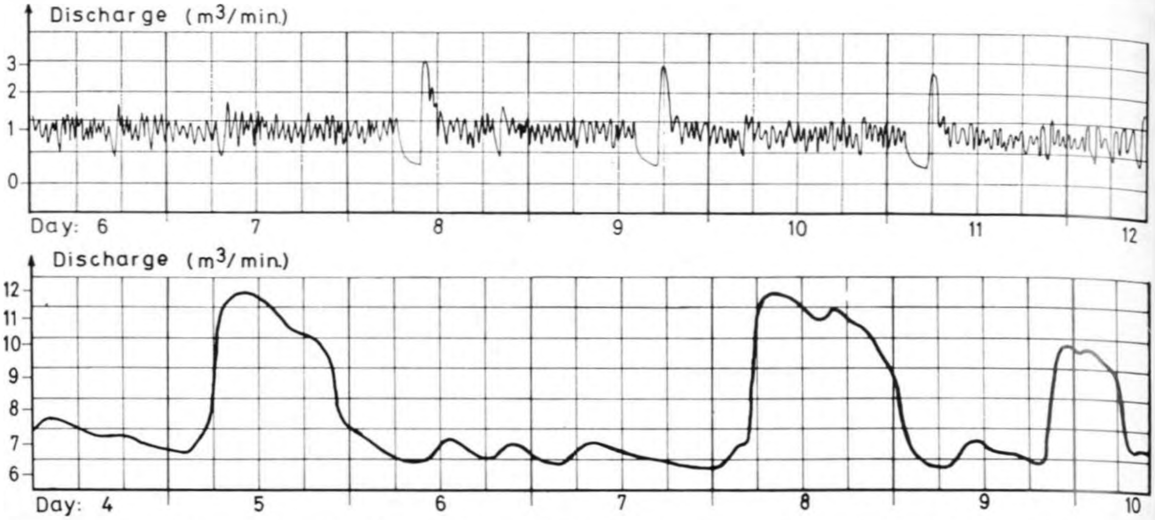


Fig. 6. Records of the Jósvafő siphonic springs. The triple siphon system of the Lófej Spring is in the main corridor leading to the spring. At the Nagy Tohonya Spring a single side-corridor siphon is producing the outbursts. Onto this discharge time-series is superimposed the series of pulsations generated by the Lófej Spring. Top: the discharges of the Lófej Spring in May 1980. Bottom: the discharges of the Nagy Tohonya Spring in May 1976

The effect of a more distant siphon is also apparent in changes of yield that occur at Nagy Tohonya Spring. The water produced by the siphon outbursts of Lófej Spring enter the water system of Nagy Tohonya via swallow holes at a distance of 3 km. According to observations by *Szilvay* (1966), the outburst pressure waves (in the form of discharge pulsations) are delayed by about 4 hours in their arrival at Nagy Tohonya Spring. The average duration of discharge pulsations is 18 hours *(Fig. 6)*.

Tidal effects

The statistics of these siphon outbursts show that they occur with 30% probability close to 6, 12, 18 and 24 hours *(Fig. 7)*. It can further be proved that their frequency increases at the new moon and the full moon. *Maucha* (1965) supposed that the effect s produced by lunisolar fluctuation of vertical karst oints and demonstrated this in Vass Imre Cave, with the cooperation of *Gádoros* and *Sárváry*, in 1965. *Gádoros* (1964) had already observed discharge oscillations at Kis-Tohonya Spring which were later found to be caused also by tidal effects. *Gerber* (1965) and *Csaba* (1974) found evidence of tidal effects in karst water observation wells *(Fig. 8)*.

Air temperature effects

At the Jósvafő Research Station it was observed that during the period of snowmelt, fluctuations of air temperature and insolation cause periodic melts which in turn result in discharge oscillations *(Fig. 9)*. Other relationships for discharge measurement data will be presented in Chapters 4 and 5.

Correlations of discharge and water quality

The fundamental researches were carried out by *Kessler* (1954), *Jakucs* (1960) and *Balázs* (1964). The saturation state of spring waters, the changes

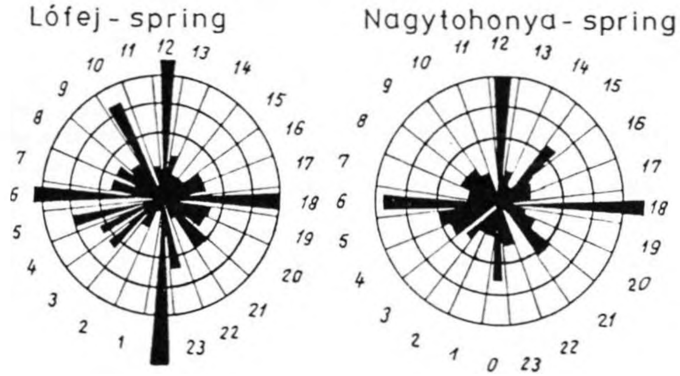


Fig. 7. Hourly distribution of the times of siphonal activity in the Lófej and Nagy Tohonya Springs (based on the statistical processing of 175 resp. 128 eruptions)

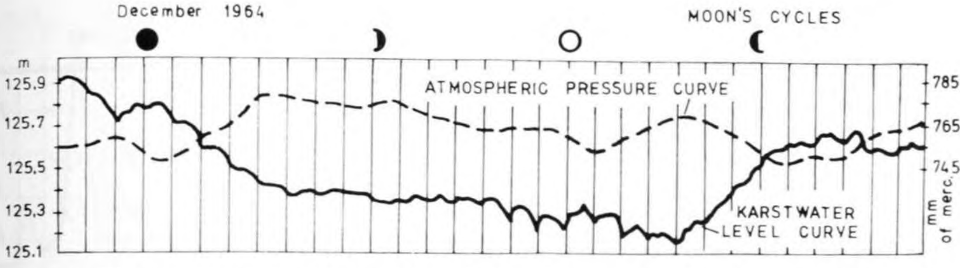


Fig. 8. The karst water levels recorded in the Tatabánya 1 Well — changes related to the periodicity of athmospheric pressure and tidal forces (after P. Gerber)

of solute composition in time and problems of the Ca/Mg ratio were studied in detail at the Research Station by *Cser*. Correlations between changes in discharge and water quality were established at several springs using weekly chemical analyses by *Izápy* (1983) in a joint work with *Maucha* within the framework of the VITUKI programme. It turned out that during floods the really significant effect is the change of Ca ion content in parallel with discharge and the inverse change of the Mg ion *(Fig. 10)*. The causes may be best understood by taking into consideration flow system data in the last column of *Table 2*. In the piezometric system not only the cold but also the warm components of the water will increase in response to a rise of the karst water level *(Gádoros 1966)*. Waters ascending from the zone below the level of the spring (stagnant and thus warmer) have higher Ca concentrations and in Jósvafő these ascend from a zone with less dolomite than in the zone of descending waters. Existence of this warm water component is supported by the fact that the average water temperatures occurring near base flow are higher than those of the multi-year mean temperature of the region.

Correlations of spring discharge and water quality were first investigated properly by *Gádoros* (1961), who found an inverse relation at Nagy-Tohonya Spring.

3. Results of research on ascending thermal karst waters

Investigation of thermal springs

The thermal springs in the country originate from the deep karst masses buried under thick cover formations, as mentioned in the Introduction.

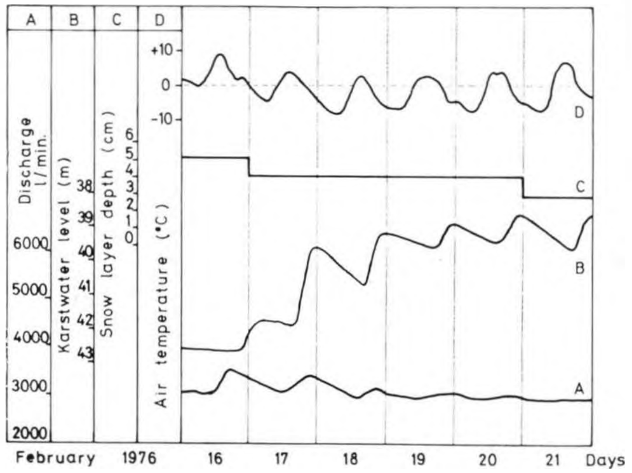


Fig. 9. The changes of the daily air-temperature and isolation causing periodical changes in snow-melt, infiltration, karst water level and discharge of the Nagy Tohonya Spring. A = discharges — Nagy Tohonya Spring (l/min), B = Szelce Valley karst water observation well — water level (m) under the orifice of the casing, C = decrease of the thickness of snow spots (cm) at the Jósvafő Research Station, D = air temperature (°C) at the Jósvafő Research Station

Before 1950 recharge of these thermal water resources was attributed to so-called "juvenile water" *(Pávay—Vajna 1950)*. Other important researchers on the thermal water springs *(Vendl* and *Papp, 1928—1962)* dealt with their hydrogeological characteristics in several papers. *Vendel* and *Kisházi* (1963) were the first to develop a theory of "underflow" based on the heat lift effect, explaining that the ascending karstic spring waters were being heated by the interior heat of the Earth. *Kessler* (1968) gave the first evidence to show that the thermal waters of Budapest originated from atmospheric precipitation.

Böcker, *Müller*, *Horváth* and *Sárváry* (1968) demonstrated hydraulic links between thermal springs and wells in Budapest by mutual effect experiments. At the same time *Szalontai* (1965—1975) proved by detailed water quality studies that the waters of the Budapest thermal water system belong to three main types, i.e. they originate from different source regions, partly outside of the Buda Mts. (the Pilis Mts. and Romhányi Karst area). He was the first to find correlation between discharge and water quality in this area.

The real functioning mechanism of the thermal springs was subsequently revealed by the research of *Alföldi*, *Erdélyi*, *Gálfi*, *Korim*, *Liebe* and *Lorberer*

Table II.

Characteristic hydraulic parameters of non-confined karst areas of Hungary

Channels				*Average of breadth of passage (m)*	*Mean flow velocity (m/hour)*	*Time constant of deplenishment (decrease of storage volume 1/10th) (day)*	*Fictive Darcy's flow-factor (m/day)*	*Transmissivity (for 50 m thick rock layer) (m²/day)*	*Rock type and porosity*		*Three different types of water in two hydraulic systems*	
Direction of flow	Vertical	0	Vertical infiltration in 2—3 channels	10^{-3}—10^{-1}	10^{-1}—10^{1}	$1.7\cdot10^{2}$—10^{1}	10^{-2}—2.10^{0}	10^{0}—10^{2}				
	Horizontal	1	Microjoints of elementary rock blocks	10^{-4}—10^{-3}	10^{-2} —10^{-1}	$1,7\cdot10^{2}$—$3.8\cdot10^{2}$	10^{-3}—10^{-2}	10^{-1}—10^{0}	Triassic limestone 0.4—1.0%	Triassic dolomite 1.0—3.5%	Piesemometric cold and warm α-karstic waters	hydraulical-system
		2	Secondary rifts systems of elementary rock blocks	10^{-3}—10^{-2}	10^{-1}—10^{0}	2.10^{1}—$1.7\cdot10^{2}$	10^{-2}—10^{-1}	10^{0}—10^{1}				
		3	Main rifts systems with karstic channels	10^{-2}—10^{-1}	10^{0}—10^{1}	10^{1}—2.10^{1}	10^{-1}—2.10^{0}	10^{1}—10^{2}				
		4	Secondary corridor of cave with swallowhole	10^{-1} —10^{0}	10^{1}—5.10^{1}	5.10^{0}—10^{1}	2.10^{0}—2.10^{1}	10^{2}—10^{3}			"Short circuit" swallowhole β-karstic waters	
		5	Main corridor of cave with swallowhole	10^{0}— 10^{1}—	5.10^{1}—10^{2}	10^{0}—5.10^{0}	2.10^{1}—2.10^{2}	10^{3}—10^{4}				

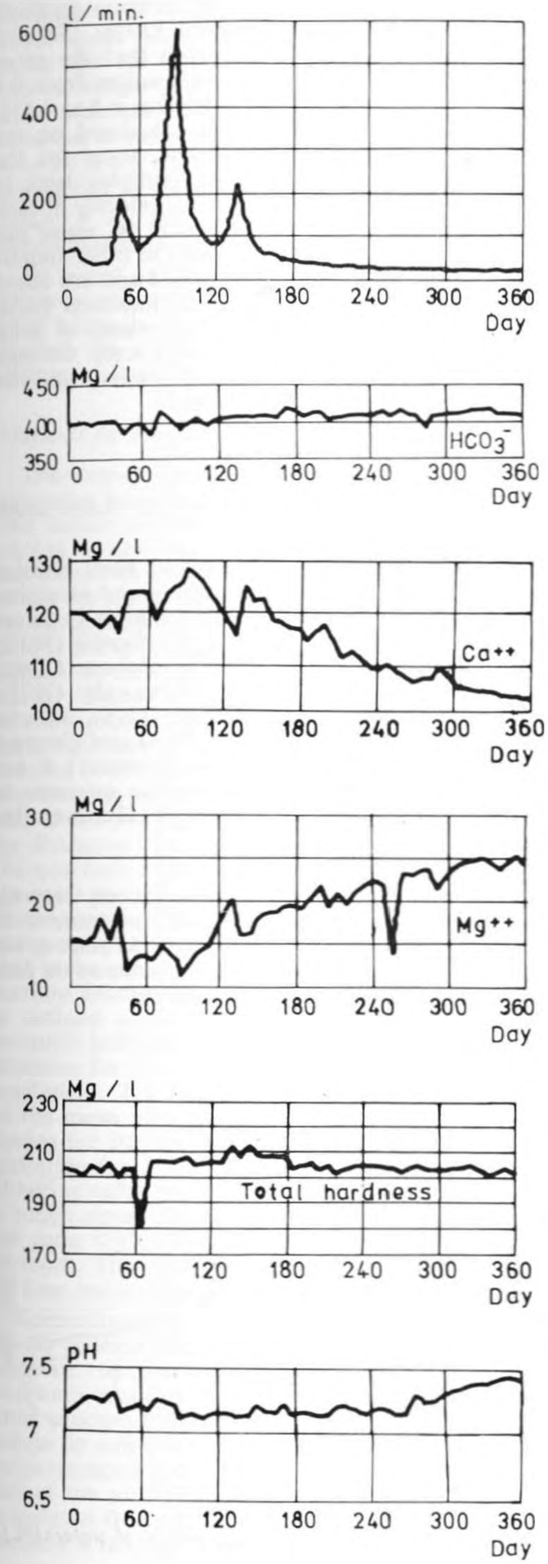
(1976—77). The essence of their "hydraulically controlled geothermal flow systems of water", is as follows: — a proportion of the water infiltrating from the recharge mountain surface will pass (flow) along deeply curved stream tubes passing through a large heat accumulation area. The velocity of this slow flow is in the order of dm/year *(Deák 1984)* and thus the water will be heated by its environment. The heated water reaches the surface again at the tops of buried domes, where it mixes with local cold waters. Thus, thermal water issues as mixed water at the surface; consequently most of our "thermal-water" springs are actually lukewarm (tepid) springs, their temperatures being below 35° C. An exception is the Héviz Lake Spring. The chemical composition of the thermal spring waters is close to that of cold karst water but contains more dissolved solids, including more trace elements. In thermal water wells (drilled wells) yet warmer and high concentrations are typical *(Fig. 11)*.

The heat output of the springs of the Transdanubian Mountain Range was investigated by *Gölz* (1982). He found that the heat capacity of approximately 90 springs warmer than 15 °C is approx. 320 MW.

4. Karst water flow — results of investigations

Tracer experiments

Research on characteristics of the subsurface flow of karst water has provided considerable know-



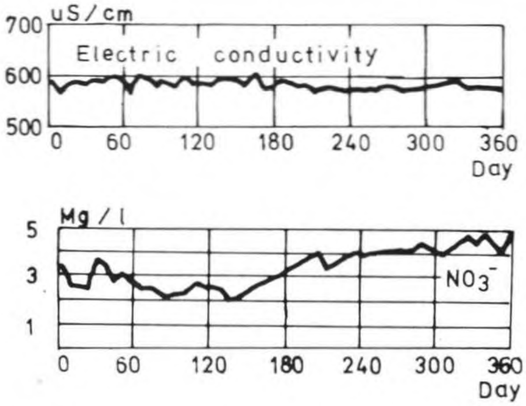


Fig. 10. Correlation of discharges and water quality changes of the Nagy Tohonya Spring — by comparison of the data-series (based on the weekly chemical analyses of G. Izápy)

ledge about several karst areas of the country. *Kessler* (1932), *Jakucs* (1952), *Balázs* (1955), *Hazslinszky* (1965), *Vass* (1966), *Rónaki* (1970), *Hőriszt* (1970), *Szilvay* (1972), *Izápy* (1978), *Dénes* (1980), *Böcker* and *Sárváry* (1968) and *Sásdi* and *Szilágyi* (1986) achieved significant results in delimiting the hydrographic systems of Hungary. In addition to the detection of caves, significant new hydraulic results were achieved in this field by the tracing experiments of *Sárváry* (1969—70) in the surroundings of Nyirád and Dorog. He determined average regional flow velocities of 0.2 m/hour between exploratory wells drilled into dolomitic terrains. Between the natural vertical shafts of the Alsó-hegy plateau and the springs there were higher velocities (*Böcker* and *Sárváry 1968*). In the joint systems of the limestone plateau mean flow velocity was 1 m/hour.

Infiltration experiments

Kessler (1956) measured the vertical infiltration velocities generated by artificially produced "rain" (sprinkling) in the *Pál-völgy* and Aggtelek (Baradla) caves. According to his results in the sample of 100 mm/hour of artificial precipitation the vertical seeping velocity varies between 1 and 5 m/hour. Similar results were achieved by *Maucha* (1980) by correlating recorded precipitation, drip rates in caves and fluctuations of karst water levels. The basic data series for these studies were recorded in the instrument park of the Jósvafő Research Station and the Vass Imre Cave, and the Szelce-völgy karstwater level observation well.

Karst water depletion studies

Discharges of the springs in Jósvafő were recorded continuously. Study of the depletion curves of the springs found that during precipitation-free periods the data series will appear as polygon-shaped and at least five sides of the polygon can be identified. This means the decreasing discharges over time can be described as the consequence of the continuously decreasing time-constant of $y = e^x$. This phenomenon was observed for the first time by *Ferenc Cser (1978)* and he used it to estimate stored water resources. According to *Maucha* (1978) the phenomenon is to be explained by the block-like structure of Jósvafő limestone karst systems. Ground plots of the caves show that the karst rock masses are dissected into 50×50 m blocks by subvertical main joint systems. From the data in Table 2 and from the depletion investigations, it can be presumed that vertical infiltration waters descend to the karst water level through the main rifts and the secondary joints within the blocks. Water then flows horizontally through the main rifts and the side and main galleries of the caves to the springs. In sequence the water content of the main galleries, the side galleries, the main rift-system, the joints within the blocks and the microfissures will be drained, one after the other. At any given instant the cavity that is draining will block flow from the smaller diameter voids that are subsidiary to it. During very dry periods the base flow will be produced by the depletion of the micro-fissures.

Space image interpretation (and use of other remote sensing methods also) was initiated and practised in karstic areas by *Rádai (*1969).

Representative hydraulic parameters

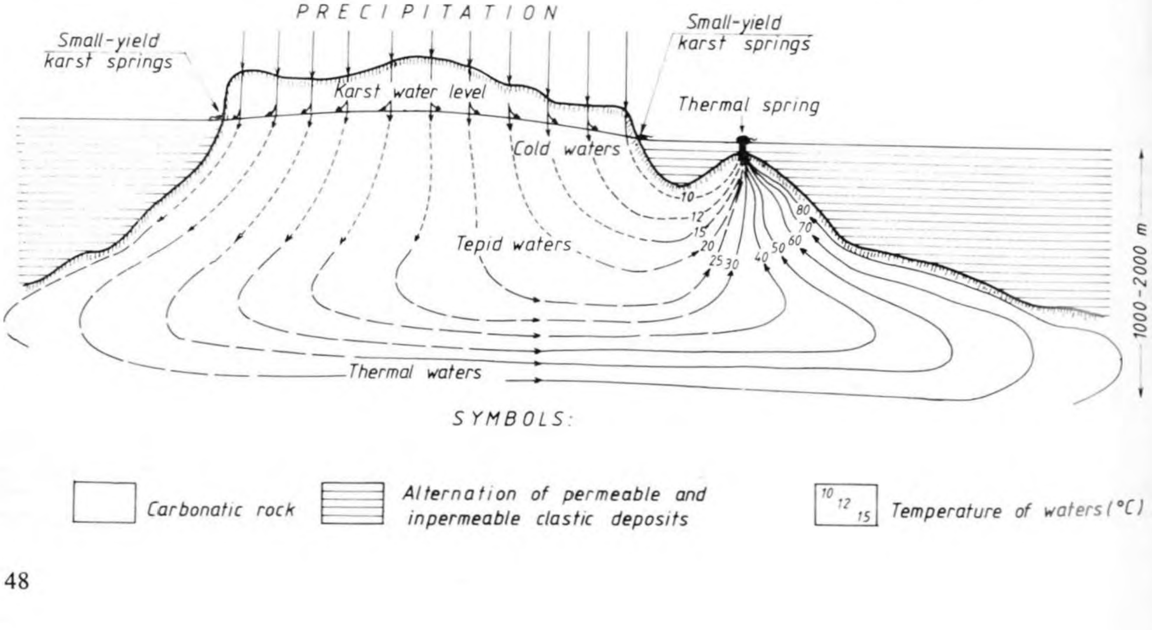
Research on the laws of karst water movement have resulted in the determination of the most important hydraulic parameters in our country. *Öllős* (1965), *Böcker* (1976), *Schmieder* (1976), *Sárváry* (1969) and *Maucha* (1980) showed that the gross porosity of the Triassic limestones ranges from 0.4 to 1%, while that of Triassic dolomites is 1 to 3.5%. The values for limestones were calculated on the basis of depletion of rock volume, those for the dolomites were computed from pumping tests in water level observation wells. The velocity of flow of thermal waters are derived from ^{14}C water age determinations *(Deák 1984)*. All the other important factors are presented in Table 2 and are based on the block-structure model of limestone karst *Böcker* (1976) discovered the importance of joint and fault systems (which vary in scale through several orders of magnitudes) in our karsts and has obtained a number of new results.

5. Water budget investigations

Water resources and balance of the karst areas of Hungary

The water balances of individual karst terrains were obtained using spring discharge and precipitation data coupled with different methods to calculate the amount of infiltration, by *Kessler* (1954), *Szabó Pál* (1955), *Láng* (1972), *Jakucs* (1960), *Balázs* (1964), *Rónaki* (1976), *Szlabóczky* (1978), *Dénes* (1983), *Tóth* (1983), *Böcker* (1975), *Maucha* (1980), *Ráday* (1986), *Lorberer* (1986) and *Csepregi* (1988). After corrections (where necessary) it can be stated that the mean precipitation amounts to 650 mm/year in the karst areas of Hungary. In-

Fig 11. Theoretical hydrogeological profile of the thermal karstic system. Subsurface flow is not only occuring in the plane of the profile, but there is an arch-shaped flow out to the outmost borders of the carbonatic rock-base. Cold spring waters did originally pour large discharges at the foot of the mountains. At the peak of the karstic dome — after the breaking-through of the impermeable layers because of the transformation of the base of erosion in the depth, a stronger than the former intense deep-flow has started



filtration is 27% (180 mm/year). In the unconfined karst areas with their total infiltration area of 1,800 km² the total dynamic karst water resources can be estimated to average about 10 m³/sec. The multi-year mean karst water balance is obtained by iteration of the equation

$P = I + E + R$

that is $650 = 180 + 450 + 20$ [mm/year]

where P = precipitation I = infiltration E = evapotranspiration, R = surface runoff.

In recent years the karst water balance of the Transdanubian Mountain Range has been calculated annually by *Böcker* and *Lorberer* in order to protect the Hévíz Lake Spring and the thermal springs of Budapest.

Methods for computing infiltration

The ever-increasing exploitation of karst water resources has made it necessary to develop new and better methods for the calculation or forecasting of amounts of infiltration. All the methods mentioned define the annual infiltration as a total of the spring discharges in a given catchment area, including the actual base flow. The values calculated here relate to the limestone karst areas; on dolomite karsts only multi-annual averages will give a correct answer. *Kessler's* method (1954) for the calculation of the representative infiltration percentages started from the rate of precipitation for the first four months of the year and that for the whole year. He corrected to allow for remaining moisture at the end of the previous year and calibrated the method by discharge time series. *Böcker* (1965) substracts the quarterly evapotranspiration runoff losses from the total precipitation received during each quarter of the year to obtain total annual infiltration. Evapotranspiration and runoff are computed from drip measurements in the Bükk Mountains. In one method used by *Maucha* (1987) annual infiltration is defined as the total of monthly infiltration, monthly infiltration being the product of the infiltration for the month and a monthly infiltration coefficient. The infiltration coefficient is the ratio of the mean monthly discharges of Nagy Tohonya Spring for 20 years and the some figure of the precipitation for Jósvafő catchment. The monthly infiltration value produced this way represents only a rough approximation of annual infiltration, like the ratio $C^2/2{,}500$ (the base quantity of the other method). The multi-year rough value is actualised by four water budget corrections.

Corrections are calculated by both of the methods, applying the monthly data of precipitation and air temperature. *Csepregi* (1988) adopted Morton's method for karsts. From the monthly total precipitation and the total of soil moisture values he subtracts the total of the monthly mean evapotranspiration and the maximum water capacity of the soil. The monthly infiltration values are calculated from the sums of monthly values. The method is not yet calibrated for karst terrains.

6. Chemical transport investigations

Denudation and environment pollution of karst areas in Hungary

In 1983—1984 VITUKI carried out investigations in three representative water quality areas in order to find characteristic water quality constituents representative for all kinds of karst water types in the country *(Table 1)*. In the Jósvafő area *Izápy* made the analyses and in the other two areas the Waterwork Labs did the work.

Izápy and *Maucha* (1986) evaluated all the data from the Aggtelek, Bükk and Bakony representative areas. Because discharges were also known the data could be compared by calculating the average specific ion transport in kg/year/km². The areas of the three representative catchments are 80, 110 and 200 km² respectively. From the differences between the solute loadings of the infiltrating precipitation and those of the springs it was found that Ca, Mg and HCO_3 ions are dominant; Na, K, Cl, SO_4 ions contribute a total of 6 to 8% of the load. 20% of dissolution occurs below soil depth according to the estimate of *Balázs* (1964). The extremes of denudation rates calculated in this manner ranged between 58 and 71 tonnes/year/km² in the three areas. Nitrate compounds (major environmental pollutants) show a mean specific range of 0.9 to 3.0 tonnes/year/km². The denudation rate obtained in the Aggtelek area is twice as great as *Balázs* calculated in 1964. Since *Balázs*' work multi-year records of reliable discharge and water quality data have been collected in the framework of the activities of the measuring network of the Jósvafő Research Station and, in addition, results of other more recent researchers could be considered. The denudation values transformed into m³ are between 22 to 26 m³/year/km². The specific surface denudation is 0,032 to 0.041 mm/year for a mean precipitation of 1,000 mm/year.

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