ZÁPADNÉ KARPATY

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GEOLOGICKÝ ÚSTAV DIONÝZA ŠTÚRA, BRATISLAVA 1989

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CONTENTS

HANZEL, V.—VRANA, K.—KULLMAN, E.—DOVINA, V.—ŠKVARKA, L.: Groundwater resources in Slovakia (Czechoslovakia) 7

KULLMAN, E.: Hydrological balances in fissure-karst hydrogeologic structures 25

JETEL, J.: Relationship between hydrogeochemical characteristics of near-surface zone of rock massif and hydrodynamic conditions 67

DOVINA, V.: Underground runoff from crystalline complexes of West Carpathians — results of evaluation and their possible application on solution of basical hydrogeological problems 105

HANZEL, V.—KULLMAN, E.—VRANA, K.: Contamination and Protection of Fissure-karst Waters in Slovakia (Czechoslovakia) 127

FRANKO, O.—BODIŠ, D.: Paleohydrogeology of Mineral Waters of the Inner West Carpathians 145

FRANKO, O.—BODIŠ, D.—FENDEK, M.—REMŠÍK, A.—JANČÍ, J.—KRÁL, M.: Methods of research and evaluation of geothermal resources in pore environment of Pannonian Basin 165

REMŠÍK, A.—BODIŠ, D.—FENDEK, M.—KRÁL, M.—ZBOŘIL, L.: Methods of Research and Evaluation of Geothermal Energy Reserves in a Fissure-Karst Setting of the Slovak Part of the Vienna Basin 193

MODLITBA, I.—KOVÁČIKOVÁ, M.: Engineering-geological investigation of anthropogenic deposits 207

Západné Karpaty, sér. hydrogeológia a inž. geol. 8, p. 7—24, Geol. Úst. D. Štúra, Bratislava 1989

VLADIMÍR HANZEL—KAMIL VRANA—EUGEN KULLMAN—VLADIMÍR DOVINA—LADISLAV ŠKVARKA

Groundwater resources in Slovakia (Czechoslovakia)

Abstract. The authors present quantitative and qualitative evaluation of expected natural groundwater resources in Slovakia. The evaluation is done for single geological formations and particularly for groundwater resources proved, representing total yield of significant springs, hydrogeological wells and concealed groundwater affluents to surface streams (Table 10).

The results of hydrogeological research and exploration enabled a complex evaluation of hydrogeologic conditions in geologic formations of Slovakia and the determination of expected natural groundwater resources, as well as the evaluation of groundwater resources documented in particular hydrogeologic structures and/or areas. The expected natural resources represent the total groundwater amount circulating in a structure or area. They were determined by hydrological balance based on the evaluation of groundwater runoff; derived by analogy or determined by a qualified estimation of areas where the calculation of groundwater reserves in accordance with principles of the Czechoslovak subcommision for groundwaters has not been done so far. (V. HANZEL—E. KULLMAN et al. 1984)

The expected groundwater resources documented represent the total yield of significant springs, hydrogeological wells and groundwater affluents to streams. The knowledge of hydrogeologic conditions and of groundwater resources in single areas and structures has a variable level and affects considerably the quantitative evaluation of groundwater resource in some regions and structures.

The existing results of the regional hydrogeochemical evaluation proved some specific features of geologic formations of Slovakia in respect of groundwater quality and protection.

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Groundwater resources in pre-Mesozoic formations

Pre-Mesozoic formations are characterized by a variable and complicated geologic-tectonic structure reflected in their hydrogeologic conditions. Their rock environment is generally described as slightly and poorly water-bearing.

In crystalline complexes the tectonically more disrupted granitoid rocks are more favourable for groundwater accumulation and circulation than crystalline schists. The yield of springs from crystalline complexes is mostly low, ranging from 0.1 $l.s^{-1}$ to 1.0 $l.s^{-1}$. Springs with the yield 1—5 $l.s^{-1}$ and higher occur in areas of more cracked crystalline rocks and in some regions intensely affected with fault tectonics. Poor transmissivity of the crystalline rock environment is also proved by usually low yield (0.1—0.4 $l.s^{-1}$) of wells. In hydrogeologically favourable areas the yield was 0.5—1.6 $l.s^{-1}$, exceptionally up to 3.0 $l.s^{-1}$. In some areas the crystalline complexes and hydrogeologically favourable rocks, mostly Mesozoic carbonates and Quaternary glacigenic sediments are significant in respect of groundwater resources. In crystalline complexes of Slovakia the total 7482—20 360 $l.s^{-1}$ of expected groundwater resources were calculated (Table 1). In Late Paleozoic rock complexes only Carboniferous carbonates occur as productive aquifers. In the Late Paleozoic rocks the total 479—1408 $l.s^{-1}$ of expected groundwater reserves were calculated (Table 2).

Chemical composition of groundwaters in pre-Mesozoic formations is mostly controlled by the alumosilicate character of the rock environment. The composition of groundwater formed under specific conditions in Paleozoic complexes of the Slovenské rudohorie Mts., Zemplínske vrchy hills, in Late Paleozoic complexes of the Tatricum, Veporicum and Gemericum.

Groundwaters of crystalline schists and granitoids are mostly silicatogenic and sulphide-silicatogenic. Dominant is the vague Ca-(Mg)-HCO_3 or the transitional Ca-(Mg)-SO_4-HCO_3 type of chemical composition with the T.D.S. 30—130 $mg.l^{-1}$. Sulphidogenic waters with T.D.S. 1—2 $mg.l^{-1}$ are scarce mine waters. Poor mineralization and general agressivity of the waters are unfavourable from the view of water economy.

Silicatogenic and sulphide-silicatogenic groundwaters of the Gelnica and Rakovec Groups (Slovenské rudohorie Mts.) show mostly T.D.S. ranging to 150 $mg.l^{-1}$ and Ca-Mg-HCO_3 or Ca-Mg-HCO_3-SO_4 type of chemical composition. Groundwaters associated with crystalline limestones represent the Ca-Mg-HCO_3 type with T.D.S. up to 500 $mg.l^{-1}$. Groundwaters associated with oxidized zones of sulphide mineralization with high concentrations of metal elements (Zn, Cu, Ni, Co a. o.) unfavourable for water economy, represent the Ca-SO_4 type and show the highest T.D.S. (up to several $g.l^{-1}$).

Groundwaters in crystalline complexes are mostly contaminated by precipitation (acidification, locally increasing sulphate agressivity, a. o.) and by tourism, forestry, pasturage. In some regions waters are contaminated by mining operations.

Table 1 Expected natural groundwater resources and documented groundwater resources in crystalline rock complexes

Orographic Unit	Area (km^2)	Expected natural groundwater resources ($l.s^{-1}$)	Documented groundwater resources ($l.s^{-1}$)
Malé Karpaty Mts.	281.5	183—852	58
Považský Inovec Mts.	173.6	87—383	29
Tribeč Mts.	199.4	184—568	61
Strážovské vrchy hills (Suchý and Malá Magura Mts.)	144.8	73—435	22
Žiar Mts.	62.6	33—186	12
Malá Fatra Mts.	203.0	406—1159	130
Veľká Fatra Mts.	71.4	143—357	48
Západné and Vysoké Tatry Mts.	379.7	1077—2278	320
Starohorské vrchy hills	13.2	28—39	12
Nízke Tatry Mts.	632.9	1184—3113	442
Veporské vrchy hills, Stolické vrchy hills and Revúcka vrchovina upland	1624.5	2901—7284	335
Volovské vrchy hills	1131.4	1131—3394	123
Branisko and Čierna hora Mts.	104.2	52—312	16
Total	5022.2	7482—20 360	1608

Table 2 Expected natural groundwater resources and documented groundwater resources in Late Paleozoic rock complexes

Orographic Unit	Area (km^2)	Expected natural groundwater resources	Documented groundwater resources ($l.s^{-1}$)
Malé Karpaty Mts.	35.4	18—53	7
Považský Inovec Mts.	43.7	13—57	4
Tríbeč Mts.	49.5	30—50	12
Malá Fatra Mts.	10.5	5—16	3
Nízke Tatry Mts.	260.8	209—574	237
Starohorské vrchy hills	22.5	11—35	5
Veporské vrchy hills, Stolické vrchy hills and Revúcka vrchov. upland	286.7	115—402	47
Volovské vrchy hills	170.1	51—153	20
Branisko and Čierna hora Mts.	41.5	12—33	5
Zemplínske vrchy hills	50.4	15—35	3
Total	971.1	479—1408	343

Groundwater resources in Mesozoic sediments

Besides Quaternary sediments the Mesozoic sediments contain the most part of groundwater reserves utilizable in Slovakia. The sediments consist of rocks with variable permeability, mostly of water-bearing carbonate complexes represented by Middle and Upper Triassic limestones and dolomites, and partly of water-bearing Jurassic and Lower Cretaceous limestones. In the West Carpathians the total area of water-bearing complexes is about 3280 sqkm (KULLMAN 1964). The fault and fold tectonics in the West Carpathians enable delimitation of plentiful hydrogeologic structures in the Mesozoic as well as evaluation of expected groundwater resources in single hydrogeologic structures of orographic units. In the Slovak Mesozoic there are 80 hydrogeologic structures (groups of hydrogeologic structures in the Slovak karst) whose areas have been evaluated. Groundwater resources and expected natural groundwater resources in the structures have been determined. Documented resources in hydrogeological structures represent the amount of groundwaters recorded in springs, quantitative-documented groundwater inflows to surface streams and proved by pumping tests in wells. Data on evaluated hydrogeologic structures in orographic units are presented in Table 3. The wide range of yields of documented resources is mainly due to fluctuating karst springs yields. Because of impossible complete utilization of concealed groundwater inflows into surface streams, non-economical utilization of some smaller springs and because of extremely variable yields of most springs, the resources documented cannot be regarded as utilizable groundwater resources. Most of them are at the bottom limit in Table 3 or even lower.

The data in Table 3 show that the area of 3082 sqkm was evaluated from the total area (3.280 sqkm) of aquiferous Mesozoic carbonate sequences in hydrogeologic structures. The rest represents the total amount of small areas of aquiferous carbonates, partly in regions of complicated tectonic conditions. In 80 hydrogeologic structures evaluated the total amount 27 474—31 523 $l.s^{-1}$ of expected natural groundwater resources was found out. This in average corresponds to the specific groundwater runoff 8.9—10.2 $l.s^{-1}.km^{-2}$. The specific runoff increases with the altitude of hydrogeologic structure. In low situated structures (average altitude 500 m) it is about 8.0 $l.s^{-1}.km^{-2}$ in average, in medium altitudes (625 m) — about 12.0 $l.s^{-1}.km^{-2}$ and in high-situated hydrostructures (960—1100 m) the specific groundwater runoff is 14.0—17.0 $l.s^{-1}.km^{-2}$ (Kullman 1986). Former data on the groundwater specific runoff (8—10 $l.s^{-1}.km^{-2}$) and the calculated total amount of natural groundwater resources (26.2—32.8 $l.s^{-1}$, Kullman 1964) show that generally natural groundwater resources are higher and near the top limit of the evaluation made in 1964. In the same structures 12 996—21 236 $l.s^{-1}$ of groundwater resources were calculated. It is about 58 % of expected natural resources.

Carbonatogenic waters resulting from the dissolution of limestones and dolomites represent the dominant genetic type of Mesozoic groundwaters. Their

Table 3 Expected natural groundwater resources and documented expected resources in Mesozoic hydrogeologic structures of single orographic units

Orographic unit	Area (km^2)	Expected natural groundwater resources ($l.s^{-1}$)	Documented groundwater resources ($l.s^{-1}$)
Pezinské Karpaty Mts.	115.0	917—1627	651—1361
Brezovské Karpaty Mts.	116.0	950	645—918
Čachtické Karpaty Mts.	53.6	450	337
Inovec Mts.	131.5	814—888	412—504
Tribeč Mts.	110.7	614—654	397
Žiar Mts.	19.2	180—190	108—224
Strážovské vrchy hills	378.0	3580—3780	1643—2146
Malá Fatra Mts.	119.4	1396—1506	484—1590
Veľká Fatra Mts.	361.7	4330—4480	1724—3088
Nízke Tatry Mts. — sev. časť northern part	397.5	2980—3070	1523—4242
Nízke Tatry Mts. — juž. časť southern part	130.6	1175—1313	1073—1115
Zvolenská kotlina basin	50.5	400—500	139—271
Veporské vrchy hills	10.0	80—100	15—30
Chočské vrchy hills	71.4	924	618
Belianske Tatry and northern slopes of Vysoké Tatry Mts.	99.0	3100	551
Branisko Mts.	19.2	187	142
Čierna hora Mts.	90.0	397	106
Muránska planina plateau	148.1	1826	629—1787
Slovenský raj Mts.	224.6	1767	745
Galmus Mts.	46.7	304—394	188—198
Slovenský kras (Slovak karst; groups of hg. structures)	389.0	3420	866
Total	3081.7	27474—31523	12996—21236

chemical composition is mostly Ca-HCO_3 or Ca-Mg-HCO_3 (circulations in limestones, mixed circulations in limestones and dolomites), scarcely Mg-HCO_3 (circulations in dolomites). T.D.S. range from 0.1 to 1.0 $mg.l^{-1}$ with the maximum frequency (56 %) from 300 to 500 $mg.l^{-1}$ (Gazda — Hanzel 1980). Groundwaters associated with lithofacies comprising gypsum and anhydrite (mainly Permian and Lower Triassic, less Carpathian Keuper; Gazda—Kullman 1964) have a chemical composition close to the Ca-SO_4 type. The formation of chemical composition dominantly affected by the solution of sulphates results in sulphatogenic waters of the Ca-SO_4 type with T.D.S. up to 3 $g.l^{-1}$, at concentrations of SO_4^{2-} even 1.5 $g.l^{-1}$. When carbonatogenic waters are not associated with the Permian—Werfenian gypsum-bearing formation or Carpathian Keuper, the Ca-SO_4 component usually does not exceed 20 eq%. This represents maximum 30 $mg.l^{-1}$ SO_4 concentration.

In respect of the CSN 830611 ("Drinking water") the Mesozoic carbonatogenic groundwaters in the West Carpathians represent high-quality drinking water resources as far as their petrogenic character is preserved i. e. without anthropogenic influences. Deacidification for agressive CO_2 is mainly desirable in groundwaters of fissure-karst circulations, containing even about 20 mg . l^{-1} of agressive CO_2. Sulphatogenic groundwaters are unfavourable for water economy because of their high sulphate content.

Groundwater resources in Paleogene sediments

A great part of the Slovak territory consists of the Flysch Belt Paleogene sediments and Inner Carpathian Paleogene sediments.

Sediments of the Flysch Belt are generally regarded as poorly water-bearing. It is because of impermeable claystones alternating with partly permeable sandstones. Transmissivity is higher in areas of sandstones folded into synclinal belts. The yields of fissure springs and fissure-stratal springs are usually low in the Flysch Belt (below 0.1—0.2 l . s^{-1}, under more favourable conditions — up to 1.0 l . s^{-1}, and more). Specific yields of wells range from 0.01—0.03 l . s^{-1} . m^{-1}, exceptionally 0.1 l . s^{-1} . m^{-1}. The minimum specific runoff in an environment with claystones dominant over sandstones is about 1.0—1.29 l . s^{-1} . km^{-2} and at equilibrated sandstones/claystones ratio — about 1.3—3.47 l . s^{-1} . km^{-2} (Zakovič 1980).

In the western part of the Flysch Belt 2940—7996 l . s^{-1} of expected natural groundwater resources were calculated. 623.0 l . s^{-1} of this amount were documented in significant springs concealed overflows into surface streams and in wells (Table 4).

In the eastern part of the Flysch Belt 7335.0 l . s^{-1} of expected natural groundwater resources were determined on the total area of 4695.0 sqkm. From this amount 398.0 l . s^{-1} represent documented groundwater resources (Tab. 5).

The narrow Klippen Belt has particular hydrogeologic conditions. Mesozoic klippes are small, deposited in an impermeable plastic envelope and generally poor in groundwaters. Interesting are only a group of the Vršatec klippes with the total yield of 3 springs 9.8—11.9 l . s^{-1}, the Manín klippe with the spring yield 40.3—158.2 l . s^{-1}, and the Pieniny Klippen Belt with the total yield of two springs 21.0—41.0 l . s^{-1}.

In the Inner Carpathian Paleogene the basal and sandstone formations are interesting for hydrogeology. The rock complex of the claystone, claystone-sandstone and sandstone-claystone formations are insignificant.

The basal formation in tectonically pre-disposed zones, frequently extending to the basement and enabling groundwater ascent from Mesozoic underlying limestones and dolomites, transmisivity. The basal formation is drained by springs with the yield 5—30 l . s^{-1} and more. Wells in areas of tectonic lines revealed yields ranging from 13.0 to 37.0 l . s^{-1}. The sandstone formation shows

Table 4 Expected natural groundwater resources and documented groundwater resources in Paleogene sediments of western Flysch Belt

Orographic unit	Area (km^2)	Expected natural groundwater resources ($l.s^{-1}$)	Documented groundwater resources ($l.s^{-1}$)
Biele Karpaty Mts.	598.5	479—1436	143
Javorníky Mts.	762.6	534—1678	125
Turzovská vrchovina upland and Jablunkovské medzihorie Mts.	199.5	180—360	42
Kysucké Beskydy Mts. and Kysucká vrch. upland	423.2	339—1100	93
Oravské Beskydy, Podbeskydská brázda furrow, Podbeskydská vrch. upland and Oravská Magura Mts.	756.5	1408—3422	220
Total	2740.3	2940—7996	623

Table 5 Expected natural groundwater resources and documented resources in Paleogene sediments of eastern Flysch Belt

Orographic unit	Delimitated part	Area (km^2)	Expected natural groundwater resources ($l.s^{-1}$)	Documented groundwater resources ($l.s^{-1}$)
Pieniny Mts.	Mesozoic carbonate compl.	7.0	50.0	27.0
	rest of mountain range	55.6	100.0	40.0
Ľubovnianska vrchovina upland	entire mountain range	180.0	180.0	20.0
Čergov Mts.	entire mountain range	310.0	775.0	96.0
Nízke Beskydy Mts.	Topľa river basin	1252.5	2250.0	50.0
	Ondava river basin	1205.0	2170.0	115.0
	Laborec river basin	1297.5	1430.0	10.0
Bukovské vrchy Mts.	entire mountain range	387.5	380.0	40.0
Total		4695.0	7335.0	398.0

the greatest aquosity among other Flysch sediments of the Inner Carpathian Paleogene. Yields of significant springs range from 1 to $10\,l.s^{-1}$, in exceptional cases from 10 to $46\,l.s^{-1}$. Wells proved the yields 1.2—$8.7\,l.s^{-1}$, in some cases $20\,l.s^{-1}$. In the Inner Carpathian Paleogene 5586—$8755\,l.s^{-1}$ of expected natural resources have been determined, $1562{,}0\,l.s^{-1}$ of them have been documented in significant springs, overflows into surface streams, and in hydrogeological wells (Tab. 6).

Owing to the heterogeneous mineralogical-petrographical character of aquifers (basal conglomerates with carbonate and silicate pebbly material, polymineral claystones, sandstones with a sandy or calcareous component and a variable content of sulphidic — and sulphatic sulphur) the formation of Paleogene groundwater chemical composition is mainly influenced by the solution of carbonates, hydrolytic decomposition of silicates and oxidation of sulphides. Claystones support intensive ion-exchange processes (increasing Na-HCO_3 component in chemical composition of waters). Groundwaters of carbonatogenic, carbonate-silicatogenic, partly also silicatogenic types with the Ca-(Mg)-HCO_3 type of chemical composition are generally dominant. Among other components the Ca-SO_4 is most frequent. T.D.S. range from 300 to $700\,mg.l^{-1}$, lower T.D.S. (about $300\,mg.l^{-1}$) are characteristic of groundwaters in the Flysch Belt Paleogene. Deeper parts of the Paleogene contain hydrosilicatogenic waters of the Na-HCO_3 type and marinogenic waters of the Na-Cl type, with T.D.S. ranging to several tens of $g.l^{-1}$.

As regards quality, carbonatogenic waters in the Paleogene are most favourable because both their Mn and Fe contents are only associated with groundwaters contaminated by anthropogenic factors. The increased NH_4^+ and HPO_4^{2-} contents result mostly from biochemical decomposition of natural organic matter in water circulation.

Groundwater resources in Neogene volcanics

At the inner side of the Carpathian Mountains there are Neogene volcanics genetically related with tectogenesis.

Slovak Neogene volcanics cover the area 5200 km^2. Petrochemical character of the rocks belongs to the calcium-alkaline association represented by the andesite-rhyolite and alkaline basalt association.

The volcanic complex of a stratovolcanic structure is built up dominantly by volcanoclastic rocks and lava flows. Small intrusions are concentrated in areas of volcanic centres.

The total thickness of the complex is 600—1000 m. The complicated Miocene-Pliocene block tectonics resulted in varied mosaic of tectonic depressions and elevations limited by fault systems of variable importance. Many of the faults separate blocks of different structure, containing different complexes and

Table 6 Expected natural groundwater resources and documented resources in Inner Carpathian Paleogene rock complexes

Orographic unit	Area (km^2)	Expected groundwater resources ($l.s^{-1}$)	Documented groundwater resources ($l.s^{-1}$)
Žilinská kotlina basin and Súľovské vrchy Mts.	300.9	464—736	378
Oravská vrchovina upland, Skorušinské vrchy Mts. and adjacent part of Podtatranská brázda furrow	407.6	610—1044	423
Spišská Magura Mts. and adjacent part of Podtatranská brázda furrow	418.1	199—385	52
Levočské vrchy Mts., Bachureň, Šarišská vrchov. upland, Spišsko-šarišské medzihorie (median mass)	1483.2	2939—4193	460
Turčianska kotlina basin	96.2	58—106	12
Liptovská kotlina basin	556.4	341—587	70
Popradská kotlina basin	440.8	291—585	35
Hornádska kotlina basin	339.2	358—611	42
Bánovská kotlina basin	102.3	163—225	30
Hornonitrianska kotlina basin	82.1	66—107	23
Zvolenská kotlina basin (Bystrické podolie valley) and adjacent eastern part of Kremnické vrchy Mts.	13.4	27—40	12
Horehronské podolie valley (Breznianska kotlina basin)	17.4	14—23	8
Myjavská pahorkatina upland	66.7	40—80	12
Malé Karpaty Mts.	16.8	7—20	3
Považský Inovec Mts.	6.0	9—13	2
Total	4347.1	5586—8755	1562

facies reflecting a particular hydrogeological pattern with different tectonic pulse.

Fractured rocks are generally considered as poor aquifers. All water reserves move towards discharge areas like springs, streams or wells. Yields of individual springs rarely exceed 1—2 $l.s^{-1}$. Average groundwater discharge ranges from 2 to 5 $l.s^{-1}.km^{-2}$.

Most intensive block faulting resulting in elevations (horsts) and depressions (grabens) was closely related in space and time to distribution of volcanic activity. The tectonic activity was revived along these zones in several stages. The old tectonic style was partially reactivated during Neogene volcanism and mainly later in the course of postvolcanic stabilization movements. Tectonic mobility of the blocks resulted in deep faults of regional extension (L. ŠKVARKA 1974).

Water circulation in neovolcanic rocks is mostly controlled by distribution of joints in rocks. Major faults zones controlled the stream valleys. In dry weather periods streams release groundwater from aquifers. Runoff measurements were carried out over the volcanic mountain by current-meter.

The measurements on the Neresnica stream gave the most interesting results. In two places concentrated discharge to the stream originated from a fault zone.

Near the village Podzámčok the discharge rate to the stream is $160\,l.s^{-1}$. Temperature of ascending water is 14.5 °C. Groundwater originated from an important dislocation at the depth 200—300 m and the discharge of groundwater to the stream is controlled by thermometric anomaly. The same picture was recorded near the Dobrá Niva village. Discharge rate to the stream was $46\,l.s^{-1}$, controlled by thermometric anomaly.

Occurrence of groundwaters in favourable fault zones was determined by geological, geophysical, hydrogeological, hydrological (streamflow records), geothermic and hydrochemical methods. The measurements determined the most favourable areas for high productive wells.

Specific discharge rate in wells penetrating the fault zone ranges from 10 to $20\,l.s^{-1}.m^{-1}$ per single well. The yield of wells used for watersupply is more than $50\,l.s^{-1}$. The yield is related to a regional extent of fault zones, hydraulic connection with fracture systems, porous horizons and extent of the monoclinal block sloping gently to groundwater discharge areas.

About 20 wells located in four different fault zones produced 600—$700\,l.s^{-1}$ of groundwater.

The yield of prognostic groundwater natural resources in the Slovak neovolcanic region is $8177.0\,l.s^{-1}$, of which $2560\,l.s^{-1}$ is the yield of documented groundwater resources in springs, wells, concealed affluent into surface streams (Tab. 7).

The central parts of the Štiavnické and Kremnické vrchy Mts. consist mostly of altered volcanic intrusions and are poor in more productive springs. They are drained by mining plants (about $400\,l.s^{-1}$ by the Voznica adit, about $100\,l.s^{-1}$ by the Kremnica adit, and approximately $60\,l.s^{-1}$ are pumped from the Cígeľ coal mine). In the area of the Krupinská planina (high-level plain) displaced volcanoclastic rocks mostly with pore permeability dominate. In the central part in the area of Plášťovce, Rykynčice, Medovarce the well yields range from 10 to $46\,l.s^{-1}$ and specific yields from 0.5 to $4.0\,l.s^{-1}.m^{-1}$.

Silicatogenic character of groundwaters is due to mineralogical-petrographical composition of neovolcanics (mostly andesits, rhyolites and their vol-

Table 7 Expected natural and documented groundwater resources in Neogene volcanics

Orographic unit	Delimitated part	Area (km^2)	Expected natural resources ($l.s^{-1}$)	Documented groundwater resources ($l.s^{-1}$)
Štiavnické vrchy Mts.	central part	1080	1300	450
	southern part			150
Javorie Mts.	fault line between Zvolen and Krupina	420	840	250
	the rest of mountain range			50
Krupinská planina (high level plain)	central and southern parts	1300	1040	250
	western part			100
	Ostrôžky			50
Poľana Mts.		340	750	100
Kremnické vrchy Mts.	eastern part	450	730	80
	central and southern part			120
	northern part			100
Vtáčnik Mts.	northern part	380	850	90
	southern part			150
Pohronský Inovec Mts.		230	350	100
Vihorlat Mts.	western part	460	482	100
	central part		115	90
	SE part		190	110
Slánske vrchy Mts.	northern part	540	590	90
	central part		410	160
	southern part		200	70
Total		5200	8177	2560

canoclastics, less basalts). The Ca- and Ca-(Mg)-HCO_3 type of chemical composition is therefore the basical type in neovolcanic complexes. Less significant are sulphide oxidation, solution of carbonates (mainly in tuffaceous volcanoclastics), ion-exchange and anthropogenic influence. Total dissolved solids in groundwaters with nearsurface circulation in effusive rocks are 50—200 mg.l^{-1}, in volacnoclastic sometimes even 500 mg.l^{-1}. There are different genetic conditions for groundwater chemical composition along tectonic contacts and faults. The resulting chemical composition is frequently affected by mixed shallow and deep groundwater circulations (e. g. the Neresnica fault zone S of Zvolen, the area of Pukanec-Majere a. o.). There the total dissolved solids range to 200—800 mg.l^{-1} with local variations. The Na-HCO_3 component increases with the circulation depth. In deep-circulation groundwater (low free CO_2-content, reducing environment) the Ca-SO_4 component is eliminated, pH is shifted to the alcalic area (pH about 8—9) at characteristic low T.D.S. of silicatogenic waters (200—600 mg . l^{-1}, GAZDA 1971). Chemical composition of mine waters (around Banská Štiavnica, Kremnica) has a sulphate character at total dissolved solids 1.0—2.5 g . l^{-1}.

According to the latest data normal groundwaters in neovolcanics of petrogenic character with their parameters (except locally lower T.D.S. and hardness) are suitable for drinking in accordance with the Czechoslovak standard. Recently it was found that waters in the Central-Slovak and East-Slovak neovolcanics display a considerable secondary contamination (VRANA et al. 1984, BAJO 1983), indicated by higher contents of NO_3^-, Cl^-, SO_4^{2-}, associated with agricultural activity and inhabitation of the areas.

Groundwater resources in Neogene sediments

Neogene subsidence centres were filled with molasse sediments. They occupy the southern part of Slovakia ranging there to several thousands of meters in thickness in Danube lowlands, East-Slovak lowlands). Inner depressions are characterized by small areal extent and lower subsidence intensity. They are mostly filled with terrestrial-limnic sediments and volcanic rocks.

Permeable Egerian, Ottnangian and Badenian sediments of the Ipeľská kotlina basin are in the area of Modrý Kameň, in the Horné Strháre-Trenč depression. In the Lučenská kotlina depression is a permeable basal formation on the contact with the basement. In the Rimavská kotlina basin, around Šafárikovo and Cakovo are water-bearing carbonate rocks in the basement. In the East-Slovak lowlands and in the Košická kotlina basin are permeable Upper Badenian and Sarmatian sediments with artesian waters in the Slánske vrchy hills. The Dolný Váh, Hron-Žitava and the Subcarpathian artesian regions have been distinguished in Neogene sediments of the Danube lowlands. The youngest Pliocene sediments are frequently associated with Quaternary sediments. In the Vienna Basin the most water-bearing Pliocene sediments are deposited in a lacustrine-fluvial environment.

Among inner depressions the Turčianska kotlina basin shows the greatest transmissivity. Aquifers are represented by Pliocene gravels associated with Quaternary sediments. They are recharged with affluents from Mesozoic carbonates from the adjacent mountain ranges.

Other basins show a lower transmissivity. Groundwaters accumulated in Neogene sediments are besides precipitation recharged with groundwaters overflowing from adjacent mountain ranges. Lower precipitation complicated recharge of groundwaters in Neogene sediments and caused their low specific groundwater runoff — about 1.0 l . s^{-1} . km^{-2}. In Neogene sediments of Slovakia 2385 l . s^{-1} of documented groundwater resources were calculated (Table 8).

Chemical composition of groundwaters in Neogene sediments is extremely variable. The upper parts of Neogene basins (to the depth 150—250 m) contain silicatogenic (non-calcareous, sandy aquifers) or carbonatogenic (calcareous aquifers) groundwaters of mostly Ca-(Mg)-HCO_3 type and with variable T.D.S. 400—900 mg.l^{-1}. Increased mineralizations (locally up to 1.2—1.4 g.l^{-1}) are due to anthropogenic influence. They are characterized by increased SO_4^{2-}, NO_3^-. NH_4^+, K^+ concentrations a. o. With the increasing depth the Neogene sediments show the transition of groundwater chemical composition from Ca-(Mg)-HCO_3 through Na-HCO_3 to Na-Cl type, associated with remarkable T.D.S. increase. This is closely related to the local development of marine sedimentation in single basins, and to gradual basinal desalination, freshwater sedimentation and consequent degradation of marinogenic groundwaters. Deep-seated, highly mineralized Na-Cl groundwaters are either synsedimentary relic marine waters (T.D.S. 10—30 g.l^{-1}), affected to a variable degree by infiltration, petrogenic, biogenic metamorphosis or they are the so-called infiltration brines (T.D.S. 60—130 g.l^{-1}, in places even 300—400 g.l^{-1}) which resulted from leaching of solid evaporites by marine and brackish waters or from condensation of basin waters (MICHALÍČEK 1971).

Groundwater resources in Quaternary sediments

The greatest groundwater resources in Slovakia are in Quaternary sediments. Dense and long river valleys, intermontane depressions and lowlands are filled with Quaternary sediments of different genesis, thickness and areal extent. Fluvial gravel-sandy sediments dominate over eolian, glacigenic and other sediments. Their hydrogeologic character is controlled by thickness and extent of aquiferous formations, grain-size composition of sediments by their relation to surface streams and the nature of the pre-Quaternary basement. Hydrogeologic conditions of Quaternary sediments are also controlled by neotectonics. Owing to that Quaternary sediments in some areas range to tens and hundreds of metres in thickness (the foreland of the Tatra Mts., lower parts of the Váh, Nitra, Žitava river plains, the Danube lowlands, the East-Slovak lowlands, the Záhorská nížina lowlands). The width of river plains is variable according to the geologic structure of the region crossed by the river. The width ranges from several metres in hard Paleozoic and Mesozoic rocks to several km in soft Paleogene and Neogene sediments.

Most favourable conditions for transmissivity of gravel and sandy sediments are near-surface streams where groundwaters are recharged by straight infiltration from a river. Yields of wells in river plains are frequently extremely high — 30.0 to 50.0 l.s^{-1}, and more.

Higher terraces are smaller (except lower parts of the Váh, Nitra, Hron river valleys), sediments are loamy and groundwater recharge is controlled by infiltration from precipitation and by affluents from adjacent slopes. The well yields are usually low.

Table 8 Documented groundwater resources in Neogene sediments

Orographic unit	Delimitated part	Area (km²)	Expected natural groundwater resources ($l.s^{-1}$)	Documented groundwater resources ($l.s^{-1}$)
Neogene of Trnavská pahorkatina upland	Subcarpathian artesian region	573	500	50
	area of Žitný ostrov (island)			100
	Dolný Váh artesian region			150
Neogene of Hronská pahorkatina upland		1056	640	400
Neogene of Ipeľská pahorkatina upland	Batovská pahorkatina upland	304	300	20
	central and upper parts of upland			175
Neogene of Zvolensko-Slatinská kotlina basin		645	300	100
Neogene of Žiarska kotlina basin		130	100	40
Neogene of Rimavská kotlina basin		840	450	30
Neogene of Cerová vrchovina upland		450	360	30
Neogene of Ľučenská kotlina basin		380	200	70
Neogene of Ipeľská kotlina basin		570	340	150
Neogene of Košická kotlina basin		556	300	90
Neogene of East-Slovak lowlands	area between Laborec and Čierna voda	863	400	20
	Pozdišovský chrbát ridge and Malč. tabuľa plateau			20
	W part of East-Slovak lowlands			80

Orographic unit	Delimitated part	Area (km^2)	Expected natural groundwater resources ($l.s^{-1}$)	Documented groundwater resources ($l.s^{-1}$)
Neogene of Nitrianska pahorkatina upland		430	500	200
Neogene of Turčianska kotlina basin		470	400	300
Neogene of Trenčiansko-Ilavská kotlina basin		250	100	40
Neogene of Oravská kotlina basin		230	200	20
Neogene of Vienna Basin		388	400	300
Total		8135	5490	2385

with Quaternary

Table 9 Documented groundwater amounts in Quaternary sediments

Orographic unit	Area (km^2)	Documented groundwater amount ($l.s^{-1}$)
Záhorská nížina lowlands	853.5	1 876.0
Danube lowlands	3 285.0	20 500.0
East Slovak lowlands	1 498.0	1 118.0
Podtatranská kotlina basin	328.0	225.0
Váh river basin	1 212.0	4 267.0
Nitra river basin	362.0	1 820.0
Hron river basin	747.0	1 250.0
Ipeľ river basin	254.5	145.0
Slaná river basin	324.0	237.3
Poprad river basin	54.0	161.0
Hornád river basin	221.0	1 085.0
Torysa river basin	132.0	420.0
Bodva river basin	100.0	607.0
Topľa river basin	62.0	202.2
Ondava river basin	35.0	415.3
Laborec river basin	88.0	682.2
Total	9 228.0	36 311.0

Significant groundwater resources in fluvial sediments are in the Váh river plain, namely in the Liptovská kotlina basin and in the segment between the Žilinská kotlina basin and the outlet to the Danube river, in the Nitra river plain between the town Nitra and the outlet to the Váh river, in the Hron river plain between Tlmače and Štúrovo, and in single basins, in the Poprad river plain between the villages Hniezdne and Čirč, in the Hornád river plain between Košice and the Hungarian/Slovak frontier (in the Košická kotlina basin), in the Torysa river plain between Brezovica and Sabinov, in the Bodva river plain and in other plains (Topľa, Ondava, Laborec, Cirocha rivers). The wells documented 11,517 $l.s^{-1}$ groundwaters in Quaternary sediments of river valleys (Table 9).

The most plentiful groundwater reserves are in Quaternary sediments of the Danube lowlands with their thickness ranging up to 400.0 m. Documented groundwater reserves are 20,500 $l.s^{-1}$. Specific yields of well are sometimes higher than 100.0 $l.s^{-1}.m^{-1}$. Other significant groundwater resources are in Quaternary sediments of the Záhorská nížina lowlands and in the East-Slovak lowlands with 2994.0 $l.s^{-1}$ documented groundwater reserves (Table 9).

We have distinguished two genetic water types in Quaternary sediments from the hydrogeochemical viewpoint:

a) petrogenic waters of terrace, eolian and proluvial sediments closely related to the mineralogic-petrographical character of the circulation environment;

b) fluviogenic groundwaters of alluvial plains. Their chemical composition is mostly controlled by mixing of waters of various T.D.S. and composition, less by mineralization proceeding in the system of fluvial gravel sands water. Those genetic conditions cause a characteristic spatial variability of mineralization and chemical composition of river plain groundwaters. Man is a significant factor in the formation of the variability of groundwater chemical composition (GAZDA 1974).

The mineralogic-petrographical composition of Quaternary sediments in lowlands mostly controls the basical Ca- and Ca-Mg-HCO_3 types of chemical composition of groundwaters with some local modifications, like Mg-HCO_3 type in alluvia of the rivers Váh and Žitava, or altered chemical composition to the intermediary Ca-(Mg)-SO_4-HCO_3 and mixed types due to water contamination. Under specific conditions in Quaternary groundwaters the type Na-HCO_3 forms (e. g. Neogene waters dispersion in the Vienna Basin, Danube lowland)or waters appear with a greater content of the Na-Cl component (e. g. water dispersion from the disturbed basement to fluvial sediments of the Ondava and Topľa rivers in the East-Slovak lowlands).

Quaternary groundwaters are significant for water economy but generally they are influenced by secondary factors. Total dissolved solids range from 100 to 900 $mg.l^{-1}$, in contaminated waters even 1.2—1.4 $g.l^{-1}$ with the simultaneously increasing contents of sulphates, nitrates and deterioration of organoleptic properties.

Conclusions

The evaluation of groundwater resources in Slovakia has been concentrated mainly to hydrogeologic structures and areas interesting for water economy, but only to a lesser extent to areas of less significant groundwater resources. The evaluation concerns the area of 43 420.4 sqkm of the total Slovak area of 49 025 sqkm. So the total amount of expected natural groundwater resources in single geologic formations will be higher than 101,0—127,1 $m^3 . s^{-1}$ as presented in Table 10, since the less significant areas have not been quantitatively evaluated. This amount does not comprise the expected groundwater natural resources in Quaternary sediments. So far documented expected groundwater resources in Slovakia represent 58.0—66.3 $m^3 . s^{-1}$ (Tab. 10). Basing on the evaluation of hydrogeologic conditions in single structures and of the relation between expected natural groundwater resources and documented resources a further amount of about 10.0 $m^3 . l^{-1}$ of quantitative resources (Tab. 10) so far untested, and assumption of accumulation of groundwaters and of their possible tapping may be determined.

Table 10 Expected natural and documented groundwater resources in individual geological formations in Slovakia

Geologic formation	Area (km^2)	Expected natural groundwater resources ($l . s^{-1}$)	Documented groundwater resources ($l . s^{-1}$)	Non-explored exploitable groundwaters ($l . s^{-1}$)
Pre-Mesozoic formations	5993.3	7961—21 768	1951.0	85.0
Mesozoic formations	3081.7	27474—31 523	12996—21 236	5662.0
Inner-Carpathian Paleogene	4347.1	5586—8755	1562.0	340.0
Klippen Belt and Flysch Belt	7435.3	10275—15331	1021.0	643.0
Neogene volcanics	5200.0	8177.0	2560.0	760.0
Sedimentary Neogene	8135.0	5490.0	2385.0	470.0
Quaternary formations in lowlands	5638.5	24794.0	24794.0	690.0
Quaternary formations in river valleys	3591.5	11517.0	11517.0	1635.0
Total	43420.4	101 274.0—127 355.0	58 786—67 026.0	9985.0

Significant groundwater resources in mountain ranges ascending in springs are in the most part tapped and utilized but there still are concealed groundwater reserves overflows to surface streams or from mountain ranges to sediments of lowlands and depressions. A more extensive exploitation of groundwaters in mountain ranges will be followed by decrease in groundwater reserves of Neogene and Quaternary sediments in lowlands, basins and alluvial plains. There are further reserves in regulation of exploitation mainly of fissure- and fissure-karst waters by the compensation of exploitation of accumulated groundwater reserves from favourable hydrogeologic structures.

The regional hydrogeochemical research revealed the most favourable conditions for the formation of drinking waters mainly in Mesozoic carbonate complexes, tectonically disrupted Neogene volcanics, and in Quaternary alluvia. In respect of groundwater contamination they represent the most threatened geologic environments. This is why first of all groundwaters of Quaternary formations are only utilized in a limited extent.

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Hydrological balances in fissure-karst hydrogeologic structures

Abstract. The author presents data resulting from long-term hydrologic balances of five closed fissure- and karst-fissure hydrogeologic structures. The data facilitated the precision of the values of runoff, of changes in groundwater reserves, the relationships between particular balance members and documentation of markedly higher average evapotranspiration in the entire altitude range of the structures studied (507-1 096 m) in comparison with the formerly applied values. The results of quantitative evaluation of groundwater natural resources in many West-Carpathian hydrogeologic structures are precised as well.

Introduction

Hydrogeological balances are particularly important for the study and evaluation of water circulation in hydrogeologic structures. It goes also for fissure-karst hydrogeologic structures where most hydrogeological problems (relationships between precipitation, runoff, evapotranspiration, changing groundwater reserves) of fissure-karst waters and the evaluation of natural groundwater resources may be solved by the balance evaluation of groundwaters in fissure-karst hydrogeologic structures as units* formed of fissure-karst hydrogeologic basins**.

In individual mountain ranges of the West Carpathians, owing to variable and intricate geologic structure many fissure-karst hydrogeologic structures

* The hydrogeologic structure of fissure-karst groundwater is a geologic structure mostly consisting of carbonate-rock water-bearing formations. The structure may partly consist of less permeable and impermeable formations. It may also be identical with one or more hydrogeologic basins or may display inner division into several water-bearing systems (G. CASTANY—J. MARGAT 1977).

** A hydrogeologic basin of fissure-karst waters represents a simple or complicated water-bearing environment of carbonate rocks with fissure-karst and fissure groundwaters. Groundwaters flow from the environment to one or to a group od fissure-karst groundwater issues. It is delimitated by groundwater divide (G. CASTANY—J. MARGAT 1977).

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may be distinguished. Simple hydrogeologic structures may be identical with hydrogeologic basins, and extremely complicated structures may comprise several hydrogeologic basins. Closed hydrogeologic structures are particularly significant in respect of hydrogeology and hydrology because they enable relatively exact hydrological balances, evaluation of relationships between terms of the hydrological balance equation, evaluation of natural groundwater resources as well as their changes in time. The evaluations are significant for determination of evapotranspiration values in fissure-karst hydrogeologic environments. Calculation of evapotranspiration values in closed hydrogeologic structures from hydrologic balance equation may be regarded as the most exact method considering all factors what no other calculation method can do. Solution of hydrogeological balances in closed hydrogeologic structures in various altitudes and thus documented relationships between the particular terms of the balance equation may be by analogy applied on the adjacent open hydrologic structures.

Here we present the data resulting from hydrological balance evaluations in five representative closed fissure-karst hydrogeologic structures with intensive afforestation, situated in variable altitudes. The structures were selected so as to represent the most part of fissure-karst hydrogeologic structures in the West Carpathians. The representative hydrogeologic structures were studied for a long time viz. ten hydrological observation years in average.

Classification of fissure-karst hydrogeologic structures in respect of their closing

The relation of water-bearing sequences of a hydrogeologic structure and its groundwaters as a whole to the surrounding rock environments and their groundwaters is most significant for a complex evaluation of groundwaters in karst hydrogeologic structures and for the evaluation of their groundwater resources. From this view hydrogeologic structures of the West Carpathians may be divided into two principal groups: A — closed hydrogeologic structures, B — open hydrogeologic structures, divided into three subgroups: $\mathbf{B}_1$ — inflow open structures, $\mathbf{B}_2$ — outflow open structures, $\mathbf{B}_3$ — transit structures.

A — Closed hydrogeologic structures are bordered with impermeable rocks on their periphery and in their basement. They are recharged with precipitation waters (or with recordable surface water inflow from areas out of the structure). The structures are drained in full extent by springs or surface flows without hidden groundwater runoff from a hydrogeologic structure. In closed hydrogeologic structures all inflowing and outflowing waters may be recorded by measuring the yields of springs and surface flows.

B — Open hydrogeologic structures are divided into three subgroups according to the character of their openness:

B_1 — inflow open hydrogeologic structures are bordered by impermeable formations in the basement and in the most part of their periphery. Their aquifers have a partially immediate contact with adjacent aquifers of other structures what enables the direct groundwater inflow from adjacent hydrogeologic structures into a fissure-karst hydrogeologic structure. Besides their recharge and drainage identical with those in closed hydrogeologic structures, they are also recharged by groundwater inflow from the areas out of the hydrogeologic structure. The total outflow may be recorded in springs and surface flows. The recording and evaluation of their total recharge is complicated or even obstructed by the direct groundwater inflow into a hydrogeologic structure.

B_2 — The open outflow hydrogeologic structures are bordered with impermeable formations in the areas of possible groundwater inflow into a structure. They are open in areas of groundwater outflow from the structure. Then there is unrecordable partial groundwater runoff from the structure, on its periphery or deep runoff out of the structure. The direct registration of the total groundwater runoff by measurements of springs yields and surface flows is not possible.

B_3 — Transit hydrogeologic structures are open for direct groundwater inflow into aquifers of the hydrogeologic structure and for direct runoff into aquifers of adjacent structures or for deep drainage of these structures into other hydrogeologic structures. Direct registration of total groundwater recharge and of total runoff by measurements of spring yields and of surface streams discharge is impossible.

Closed hydrogeologic structures of fissure-karst groundwaters and their utilization in the study of hydrogeology of fissure-karst waters

The West Carpathians Mts. are characterized by a nappe structure, by alternating permeable fractured and karstified Mesozoic carbonate formations and partly permeable Mesozoic formations. Fault tectonics, vertical movements along faults, supporting formation of impermeable barriers composed of crystalline rocks, Mesozoic, Paleogene and Neogene rocks resulted in many closed fissure-karst hydrogeologic structures of extent optimal for evaluation (10—150 sq km) so the West Carpathians belong among the world's most favourable areas for the study of karst hydrology and hydrogeology in respect of the evaluation of groundwater in hydrogeologic structures. These conditions enable to make almost exact hydrological balance, to study the relations between precipitation, runoff and evapotranspiration, time changes in groundwater reserves, effective precipitation, evaluation of ground- and surface water specific runoff, natural groundwater resources in hydrogeologic structures and their changes in time. The hydrogeologic structures are significant because the data

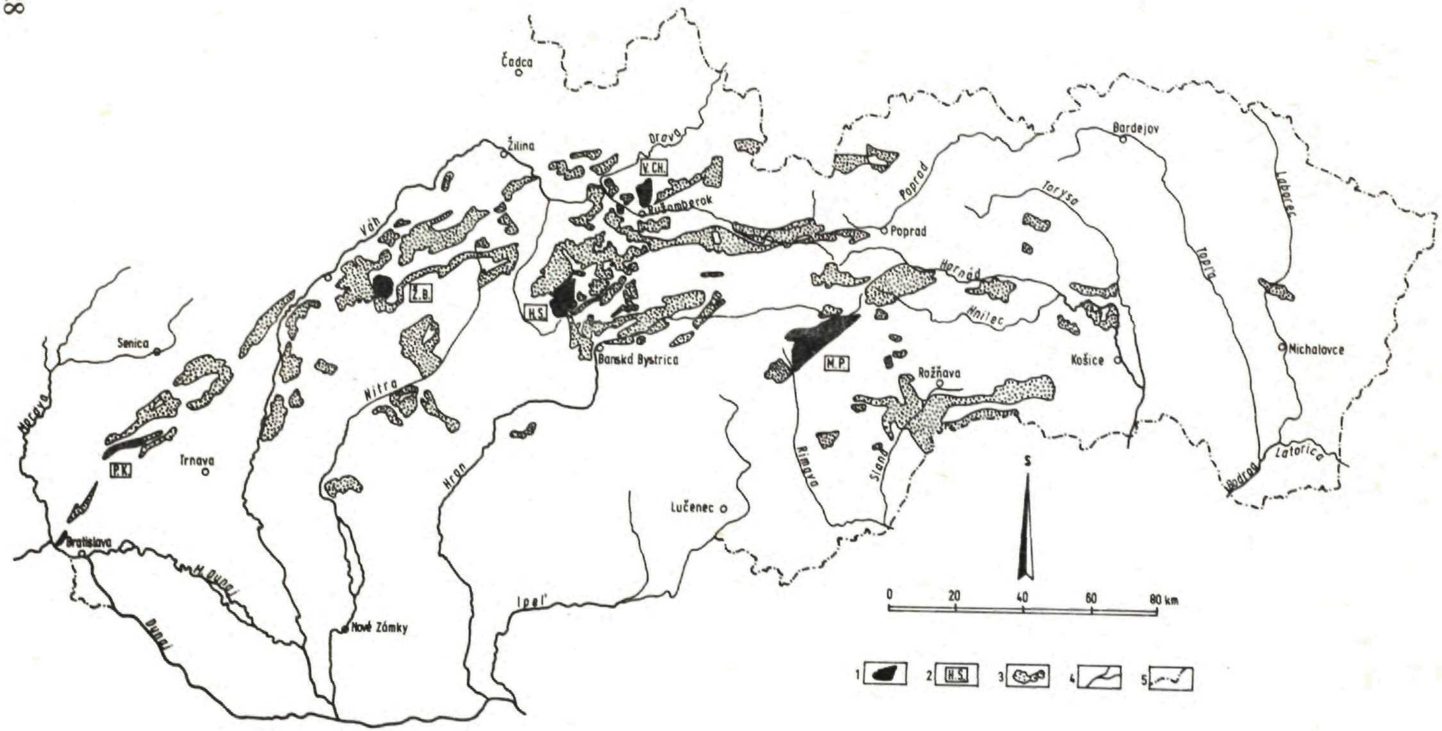

Fig. 1 Map of distribution of water-bearing Mesozoic and Paleozoic carbonate complexes in West Carpathians with marked evaluated representative closed fissure-karst hydrostructures
1 — Mesozoic and Paleozoic limestone- and dolomite water-bearing complexes with fissure-karst waters,
2 — Representative closed fissure-karst hydrogeologic structures,
3 — abbreviations denoting single representative fissure-karst structures, P. K. — Križna nappe hydrostructure of Pezinské Karpaty Mts., Ž. B. — Žihlavník-Baské hydrostructure, H. S. — Harmanec syncline hydrostructure, M. P. — Muráň plateau hydrostructure, V. CH. — Veľký Choč hydrostructure, H — surface streams, S — state frontier.

on these structures may be generalized and by means of analogy applied on open hydrogeologic structures.

Basing on the favourableness of the West Carpathians the author selected five representative closed fissure-karst hydrogeologic structures (Fig. 1). Selecting the structures, the author considered the closing of the structures and their ability to represent water-bearing carbonate complexes in variable altitudes, as well as variable degree and character of their deformation, variable regime of groundwaters, affected by their different accumulating and retarded depletion abilities. The purpose of the work was longlasting study of principal laws concerning fissure-karst groundwaters in these structures, the changes in time and their relations to precipitation, and the influence of evapotranspiration on the formation of groundwaters from precipitation.

Solving the problems, the author exploited the measurements of runoff in two closed hydrogeologic structures, and in further three selected structures he provided:

— construction of a complex of measuring devices on springs and surface streams for continuous measurement of all inflowing and outflowing waters;

— testing of closing of hydrostructures in places where geological investigations did not unambiguously proved the closing (this concerns the Muráň plateau near Zlatno);

— completion of rain gauge stations and totalizers by Slovak Institute of Hydro- and Meteorology for precision of precipitation evaluation;

— recording of all groundwater exploitations;

— elaboration of methods of the evaluation of changes in groundwater reserves of hydrogeologic structures;

— calculation of evaporation from soil surface by the Budyko-Zubenokova method.

Systematical measurements in the first two closed hydrogeologic structures lasted 9 years (1957—1965) and 11 years (1955—1965). Measurements in other three selected closed hydrogeologic structures evaluated more precisely than the former ones, started at the beginning of the hydrological year 1971 (November 1, 1970) and lasted 10 hydrological years (to October 30, 1980), i. e. a hydrological decade. The measurements resulted in rich documentation material for hydrological balance evaluation (total material from 49 hydrological years). The results follow.

Selected closed hydrogeologic structures were evaluated in respect of their altitude, geologic structure, hydrogeologic conditions, afforestation degree, composition of wood plants (coniferous, foliaceous) and slope orientation. Characteristics of these hydrogeologic structures are given in Tables 1—4.

Table 1 Characteristics of representative closed fissure-karst hydrogeologic structures

No.	Hydrogeologic structure	Localization	Area sq km	Average altitude above sea level in m	Evaluation period Number of hydrological years	Drainage mode and measurements range	Time interval of measurements	References to information on detail characteristics of hydrogeologic structures and on their evaluation
1	Dolomite-limestone monocline of Krížna nappe in Pezinské Karpaty Mts. (P. K.)	Area between villages Kuchyňa and Lošonec	12.88	507	1957—1965 8	By springs (17 measuring devices at springs)	weekly	KULLMAN 1986, 1984b, 1978, 1977, 1965
2	Dolomite-limestone block Žihlavnik-Baské in Strážovské vrchy Mts. (Ž. B.)	Area between villages Dolná Lehota, Šipkov, Slatina, Omšenie	29.62	625	1955—1965 11	By springs (8 measuring devices at springs)	weekly	KULLMAN 1986, 1961
3	Limestone-dolomite syncline Harmanec in Veľká Fatra Mts. (H. S.)	Area between Čremošné and Harmanec	27.90	963	1971—1980 10	By springs and surface streams draining groundwater (8 measuring devices at springs and on surface streams)	continuously at large springs and on surface streams, daily at small springs	KULLMAN 1986, 1982, 1980
4	Dolomite-limestone block in Muráň plateau (M. P.)	Area of Tisovec–Muráň–Švermovo–Zlatno–Závadka n. Hronom	126.13	997	1971—1980 10	By springs and surface streams draining groundwaters (34 measuring devices on surface streams and at springs)	continuously on surface streams and at large springs, daily at small springs	KULLMAN 1986, 1982, 1980
5	Dolomite-limestone block Veľký Choč in Chočské vrchy Mts. (V. CH.)	In western part of mountain range between Valaská, Dubová and Lúčky	19.45	1096	1971—1980 10	By springs and surface streams draining groundwater (5 measuring devices on surface streams and 6 water-meters registering exploitation	continuously	KULLMAN 1986 KULLMAN–ZAKOVIČ 1974

Table 2 Geological characteristics of hydrogeologic structures and their impermeable basement

No.	Hydrogeologic structure	Tectonic unit associated with hydrostructure	Tectonic type of hydrostructure	Age of formations composing hydrostructure	Geological characteristics of impermeable basement of hydrostructure and its relation to tectonic unit
1	Monocline of Krížna nappe in Pezinské Karpaty Mts. (P. K.)	Krížna nappe	Monocline disturbed by transverse NW-SE faults	Mesozoic — Middle-Upper Triassic	Albian—Cenomanian marly claystones and calcareous sandstones Malé Karpaty Group of envelope unit
2	Žihlavník-Baské block in Strážovské vrchy Mts. (Ž. B.)	Bebrava nappe, Choč nappe, Strážov nappe	flat syncline	Mesozoic — Middle and Upper Triassic	marly limestones and marlstones (Tithonian) marls with sandstone intercalations (Albian—Cenomanian) Krížna nappe
3	Harmanec syncline	Choč nappe	syncline disturbed by NW-SE and NE-SW faults, by N-S faults at NW margin	Mesozoic — Middle and Upper Triassic	marly limestones and marls (Beriasian—Barremian), schistose marlstones (Aptian—Albian) Krížna nappe
4	Muráň block in Muráň plateau (M. P.)	Muráň nappe	nappe outlier with graben in SE part	Mesozoic — Middle Triassic	calcareous claystones and sandstones (Seisian—Lower Campilian) Muráň nappe
5	Veľký Choč block	Choč nappe	nappe outlier	Mesozoic — Middle-Upper Triassic	marls and marly limestones (Tithonian—Neocomian) Krížna nappe

Table 3 Rock characteristics of representative closed hydrostructures surface

No.	Permeability	Very good — good		Medium		Poor		Practically impermeable	
	Hydrogeologic structure	limestones %	dolomites %	organodetrital and partly marly limestones %	carbonate conglomerates and sandstones %	quartzites[1], volcanoclastics of andesites[2] %	crystalline complexes %	marly limestones and marls %	shales, claystones, sandstones %
1	Monocline of Krížna nappe in Pezinské Karpaty Mts. (P. K.)	33.54	30.11	12.28	—	—	0.57	8.99	14.51
2	Žihlavník-Baské block in Strážovské vrchy Mts. (Ž. B.)	76.24	22.79	—	—	—	—	—	0.97
3	Harmanec syncline in Veľká Fatra Mts. (H. S.)	19.43	67.57	—	—	9.43[2]	—	3.57	—
4	Muráň block in Muráň plateau (M. P.)	74.55	17.29	—	—	0.75[1]	4.68	—	2.73
5	Veľký Choč block in Chočské vrchy Mts. (V. CH.)	42.81	37.44	—	0.87	—	—	18.88	—

Table 4 Afforestation and surface orientations of representative closed hydrostructures

No.	Hydrogeologic structure	Afforestation %			Bare areas %	Meadows %	Flatland	Orientation (%)							
		total	coniferous	folliaceous				N	NE	E	SE	S	SW	W	NW
1	monocline of Krížna nappe in Pezinské Karpaty Mts. (P. K.)	97.23	2.12	95.11	—	2.77	—	19.99	16.94	2.17	9.05	11.60	8.98	6.36	24.71
2	Žihlavník-Baské block in Strážovské vrchy Mts. (Ž. B.)	81.93	8.77	73.21	5.72	12.30	1.34	15.91	5.17	4.75	16.12	20.75	14.59	9.45	11.92
3	Harmanec syncline in Veľká Fatra Mts. (H. S.)	97.73	37.09	60.64	2.27	—	—	17.34	15.00	7.56	15.41	7.35	13.11	11.57	12.66
4	Muráň block in Muráň plateau (M. P.)	90.43	53.06	37.57	0.07	9.30	9.52	8.33	9.99	7.03	21.43	12.10	9.70	8.65	13.25
5	Veľký Choč block in Chočské vrchy Mts. (V. CH.)	87.32	78.45	8.87	—	12.68	—	11.33	6.38	5.18	7.16	19.09	10.01	19.69	21.16

Hydrological balance of representative closed hydrogeologic structures and its results

Methods of hydrological balance

Uniform methods were applied on all the five closed hydrostructures. The methods were based on the basic hydrological balance equation. Some equation terms are negligible in respect of particular representative closed hydrostructures and their character.

Basic balance equation:

$$Z + P_p + P_{pz} = O_p + O_{pz} + O_{pzh} + E_b \pm \Delta V_p \pm \Delta R \pm \Delta R_p$$

where Z — precipitation
P_p — surface water inflow into hydrostructure
P_{pz} — groundwater inflow into hydrostructure
O_p — surface runoff from hydrostructure
O_{pz} — groundwater outflow from hydrostructure to surface (in springs, in outflow to surface streams, groundwater amount exploited from hydrostructure)
O_{pzh} — deep groundwater outflow from hydrostructure
E_b — evapotranspiration
$\pm \Delta V_p$ — increase or decrease of water accumulation on hydrostructure surface (lakes, a. o.)
$\pm \Delta R$ — changing groundwater reserves in rock environment of hydrostructure
$\pm \Delta R_p$ — changing water reserves and humidity in soil

It is difficult to solve the hydrological balance equation in its general form without errors because of many problems. This is why representative closed fissure-karst hydrogeologic structures were selected. Then the equation may be simplified and precision may be preserved at the precision level of field measurements of the main equation terms (precipitation, inflow, outflow. The terms P_{pz} (groundwater inflow) and O_{pzh} (deep groundwater outflow) may be neglected without causing any errors. There is no surface water retention in the representative hydrostructures so the term $\pm \Delta V_p$ may be neglected as well. The term $\pm \Delta R_p$ (changing water reserves in soil and changing humidity) was abandoned. Soil cap in hydrogeologic structures of fissure-karst waters is either thin or missing so its influence on the evaluation is lowered. Still the hydrologic balance may be loaded with a small error due to neglecting this term of the balance equation.

The simplified balance equation may be applied on closed hydrostructures to balancing by single hydrological years or shorter periods. Following is the form of the simplified equation:

$$Z + P_p = O_p + O_{pz} + E_b \pm \Delta R$$

All its terms except evapotranspiration (E_b) were determined by field measurements or derived from them ($\pm \Delta R$). Evapotranspiration was numerated from the hydrological balance equation. This is regarded as the most precise method of evapotranspiration determination if measurements of other equation terms are not loaded with greater errors. This is why measurements in hydrostructures evaluated mainly in 1971—1980 were performed with the maximum precision possible.

Following is description of the determination of hydrological balance equation terms in a mode uniform for all five evaluated representative hydrogeologic structures.

Precipitation (Z)

is numerated for individual hydrostructures from precipitation isolines maps 1 : 50 000, compiled for this purpose. All older precipitation gauge stations were utilized. Some stations and totalizers were complemented. Maps of hydrological half year precipitation isolines for individual hydrostructures were compiled by PETERKA—ŠAMAJ—TOMLAIN et al. (1972—1982).

Surface water inflow to structures (P_p) and surface and groundwater outflow from structures (O_{pz})

The inflow and outflow were systematically measured in representative hydrostructures evaluated in 1971—1980. The measurements were mostly continuous (by water-stage recorders), partly (on smaller springs) daily at concrete measuring devices (spillweirs, measuring channels) constructed for this purpose; in hydrostructures evaluated in 1955—1965 and/or 1957—1965 weekly (on springs). Construction of measuring devices localized by the author according to geologic conditions was financed by Dionýz Štúr Institute of Geology from the most part. Some of them belonged to SHMÚ and other organizations. Systematical measurements for D. Štúr Institute of Geology were performed by the Slovak Institute of Hydrology and Meteorology (SHMÚ). Surface inflow was only measured in the hydrogeologic structure of the Muráň-plateau. There is no surface inflow in other representative structures. Data resulting from ten years mostly daily, partly weekly measurements on 70 devices (e. g. on 16 devices on surface streams, 18 devices on springs, records of groundwater exploitation) were computer-treated in the Slovak Hydrometeorological Institute in Bratislava, and in the "Engineering-geological and Hydrogeological Exploration" enterprise in Žilina.

The groundwater runoff was mainly determined by direct underground runoff measurements (spring yields and direct groundwater inflows to surface streams, measured at measuring devices) representing total runoff (in two hydrostructures) or the most part of the underground runoff (in other hydrostructures). This part of underground runoff was separated from surface streams hydrograms for some representative hydrogeologic structures by a simplified semilogarithmic method using depletion curves (RAMBERT 1972). This method is not quite exact but it is considering the underground runoff share in hydrogram of a river in fissure-karst hydrogeologic structures better than other methods applied in Czechoslovakia (method of FOSTER, KILLE, CASTANY—KILLE 1970, RAMBERT 1972). It is likely that the underground runoff in fissure--karst environment is underestimated by this method but it is considering the fact that time changes in underground runoff in fissure-karst hydrostructures (documented with springs) differ only slightly from time changes in surface stream runoff.

Changes of groundwater reserves in hydrogeologic structures ($\pm \Delta R$)

Evaluation of changes of groundwater reserves in hydrogeologic structures belongs among basic problems of short-term hydrological balances (e. g. for individual hydrological years). Carbonate complexes with dominant fissure permeability show a great ability of groundwater runoff compensation affecting the short-term hydrological balance as well as evaluation of relationship among precipitation, runoff and evapotranspiration.

I have proposed a new method for quantitative evaluation of groundwater reserve changes between the periods of balance evaluation (in our case between hydrological years). The method is based on the evaluation of groundwater discharge conditions in periods unaffected by precipitation, and on the application of the results upon quantitative evaluation of groundwater reserves (E. KULLMAN 1977, 1978, 1984).

When after a certain period (e. g. after a hydrological year) in the course of which the total runoff variability is controlled by uneven recharge by precipitation, the structure evaluated is not recharged by further precipitation, then its water reserves are discharged in accordance with runoff regularities represented by the depletion curve. I even suppose that in a precipitationless period the total groundwater runoff from the structure and its time changes are controlled by the degree of its filling with groundwater. In the precipitationless period the groundwater runoff means depletion of groundwater reserves accumulated in the structure in the period evaluated (e. g. in the hydrological year evaluated) as long as the state at the depletion of the structure gets identical with the state at the beginning of the period evaluated (Fig. 2).

When the depletion of the structure continues, the total groundwater runoff decreases below the initial total groundwater runoff in the evaluated period. In this case the depletion of groundwater reserves accumulated in the structure in the preceding periods (hydrological years) will take place. A reverse procedure enables quantitative evaluation of increase in groundwater reserves of a hydrostructure in the evaluated hydrological year.

This method is described in detail by Kullman 1977, 1978, 1984. It was used

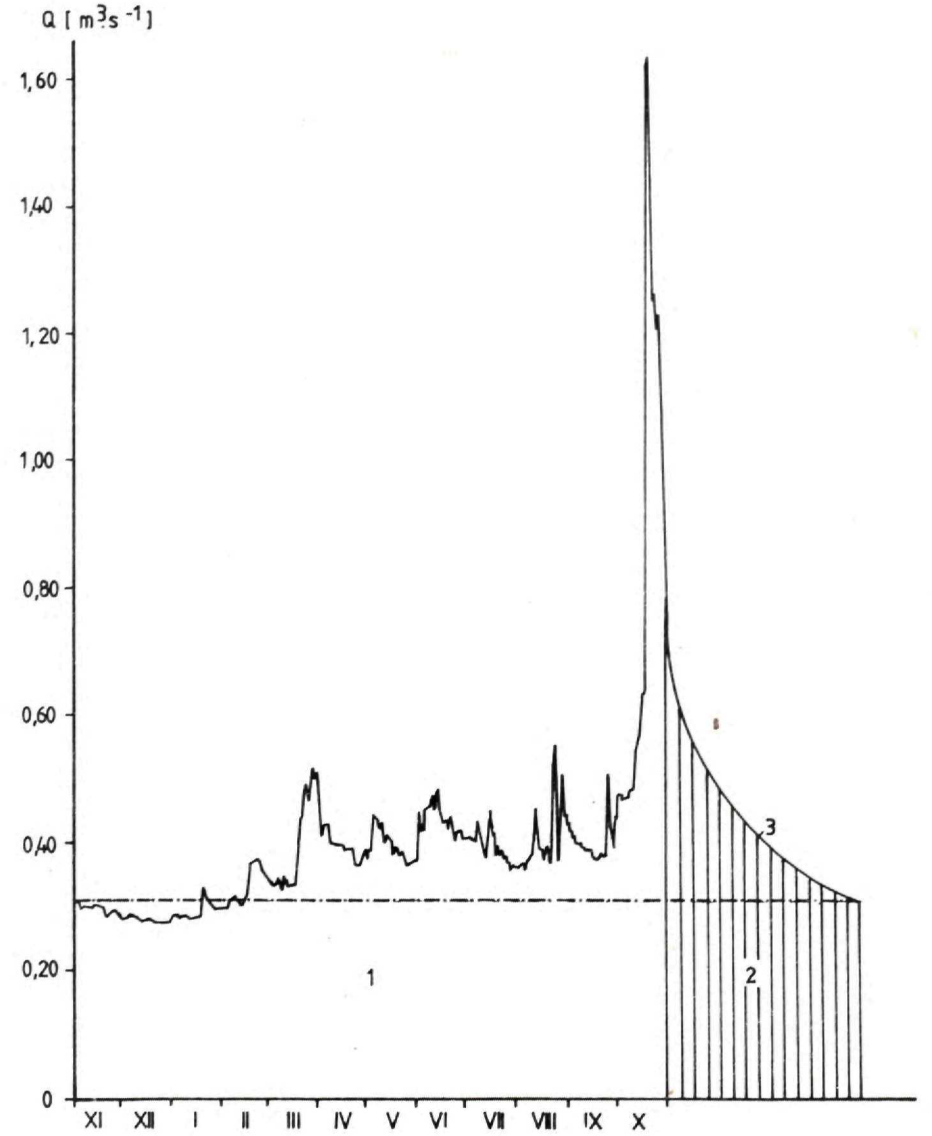

Fig. 2 Evaluation of groundwater reserves changes in hydrogeologic structure (Harmanec syncline; hydrological year 1974)
1 — course of changes in runoff from hydrostructure, 2 — groundwater reserves accumulated in hydrostructure from precipitation of year evaluated, 3 — depletion curve of waters of hydrostructure.

for calculation of groundwater reserves in all five representative hydrogeologic structures. The results are presented in the following chapters.

Evapotranspiration (E_b)

The value of evapotranspiration including snow- and ice evaporation was calculated from the balance equation for individual hydrological years, concerning all five representative hydrologic structures.

For the purpose of comparison the evaporation from soil surface was calculated by the Budyko-Zubenokova method for all structures. Soils surface evaporation isolines maps were compiled for all structures evaluated in single hydrological years, by PETERKA—ŠAMAJ—TOMLAIN et al. (1972—1981).

Results of representative closed hydrogeologic structures evaluation

Water circulation balance in hydrogeologic structures

The results of hydrological balance are presented in Table 5—9 as well as calculated terms of the simplified equation of balance for single hydrological years (in mm, $m^3 . s^{-1}$, in % of total annual precipitation). They represent information about total runoff, the underground- and surface runoffs, changing groundwater reserves, effective precipitation and evapotranspiration calculated from the hydrological balance equation, evaporation from soil surface calculated by the Budyko-Zubenokova method (TOMLAIN 1980).

Hydrological balances in closed hydrogeologic structures resulted in generally acceptable information (Tables 5—9):

— underground runoff represents the most part of total runoff and in average 29—37 percent of precipitation in low-situated hydrostructures (altitude 507—625 m); 48—49 per cent in high-situated (963—1096 m) hydrostructures;

— surface water runoff according to character of fissure-karst environment is either absent (in two hydrostructures — except rainwash water) or extremely low (in three hydrostructures) and represents in average 1.8—3.4 per cent of the annual precipitation, and 3.8—7.0 per cent of total runoff;

— specific runoff mostly consisting of underground runoff increases with altitude of hydrostructures. In low-situated (507 m) hydrostructures the specific runoff is in average $8.4 \, l . s^{-1} . km^{-2}$, in hydrostructures in medium altitude (625 m) the specific runoff ranges to $12.0 \, l . s^{-1} . km^{-2}$ in average, and from 15.1 to $17.9 \, l . s^{-1} . km^{-2}$ in high-situated (763—1096 m) hydrostructures;

— effective precipitation part in total precipitation increases with altitude of hydrogeologic structures. The effective precipitation is lowest in low-situated hydrostructure (507 m). It ranges to 29 % in average at low altitudes, to 37.1 % at medium (625 m) altitudes. High-situated (963—1096 m) hydrostructures do

not display any substantial differences between the effective precipitation share and total precipitation (47.6—48,6 %). Interesting are differences between years. They are smaller in hydrogeologic structures mostly composed of dolomites (41.7—57.6 %, Harmanec syncline hydrostructure) than in those mostly consisting of karstified rocks (Muráň plateau hydrostructure 31.6—60.0 %);
— accumulated groundwater reserves and their time changes affect differently the groundwater runoff according to hydrological character of individual structures;
— high evapotranspiration share on total precipitation in all hydrogeologic structures of fissure-karst waters with intense afforestation. Evapotranspiration represents in average 71—63 % of total precipitation in hydrostructures of low and medium altitudes, and 51—52 % in hydrostructures of great altitudes.

The results will be discussed in detail in the following parts.

Specific runoff in fissure-karst rock environment

Quantitative evaluation of groundwater natural resources belongs among basical problems of fissure-karst waters in the West Carpathians. It may indicate possible exploitation of groundwater resources. Complicated hydrogeologic conditions in the most part of open fissure-karst hydrogeologic structures do not enable direct quantitative evaluation of their groundwater natural resources. At present it is best to determine natural groundwater resources in representative closed fissure-karst hydrogeologic structures and by analogy based on thus obtained results derive the expected amount of natural ground-water resources also in complicated, unclosed hydrogeologic structures with identical climatic and hydrogeologic conditions. The evaluation should be based on information about specific runoff and groundwater specific runoff in representative hydrogeologic structures. In evaluated closed hydrogeologic structures the total specific runoff was determined by direct systematical (mostly continuous) measurements with precision at the present possible level in our country.

The groundwater specific runoff was mainly determined by direct measurements of the most part of underground runoff, and in hydrogeologic structures with partial drainage by surface streams — by separating the underground runoff from surface streams hydrograms.

The data on average annual specific runoff of groundwater and surface water in evaluated representative hydrogeological structures are given in Tables 10 and 11. All evaluated hydrogeologic structures situated in altitudes 550—1096 m displayed high specific runoff consisting completely or mostly of underground runoff. Surface runoff is either absent or extremely low. In two structures with the exception of possible rainwash water — it is absent and in tree structures it represents in average 3.8 %, 4.7 % and 7.0 % respectively of total runoff. The average runoff for the evaluated period in the lowest hydrogeologic structure (of Krížna nappe in Pezinské Karpaty Mts. — 550 m above sea level)

Table 5 Water circulation balance in hydrogeologic structure of limestones and dolomites of Krížna nappe

Hydrological year XI—X.	Dimension	Z precipitation	O_s runoff total	O_{pz} runoff underground	Total runoff on hydrological years boundary $m^3 . s^{-1}$
1957	mm $m^3 . s^{-1}$ %	956 0.3905 100.0	314 0.1282 32.8	314 0.1282 32.8	0.1074 0.0789
1958	mm $m^3 . s^{-1}$ %	869 0.3549 100.0	277 0.1131 31.9	277 0.1131 31.9	0.0691
1959	mm $m^3 . s^{-1}$ %	914 0.3733 100.0	276 0.1127 30.2	276 0.1127 30.2	0.0742
1960	mm $m^3 . s^{-1}$ %	973 0.3963 100.0	251 0.1022 25.8	251 0.1022 25.8	0.0657
1961	mm $m^3 . s^{-1}$ %	667 0.2724 100.0	209 0.0854 31.3	209 0.0854 31.3	0.0534
1962	mm $m^3 . s^{-1}$ %	719 0.2937 100.0	—	—	0.0570
1963	mm $m^3 . s^{-1}$ %	912 0.3725 100.0	261 0.1066 28.6	261 0.1066 28.6	0.0634
1964	mm $m^3 . s^{-1}$ %	854 0.3478 100.0	203 0.0827 23.8	203 0.0827 23.8	0.0825
1965	mm $m^3 . s^{-1}$ %	1015 0.4145 100.0	337 0.1376 37.1	337 0.1376 37.1	0.0755
Average 1957—1965	mm $m^3 . s^{-1}$ %	895 0.3653 100.0	266 0.1086 29.7	266 0.1086 29.7	

in Pezinské Karpaty Mts. Hydrological years 1957—1965 (Area 12.88 sq km, average altitude 507 m)

−R	+R	O_z	E_b	V_{BZ}
changing groundwater reserves in hydrogeologic structures		effective precipitation	evapotranspiration calculated from balance equation	evaporation from soil surface (by Budyko-Zubenokova method)
depletion of precipitation from preceding years	reserves transfer to following year			
39 0.0159 4.1	— — —	275 0.1123 28.8	681 0.2781 71.2	470 0.1920 49.2
9 0.0037 1.0	— — —	268 0.1095 30.8	601 0.2455 69.2	469 0.1915 54.0
— — —	10 0.0041 1.1	286 0.1168 31.3	628 0.2565 68.7	504 0.2058 55.1
20 0.0081 2.1	— — —	232 0.0945 23.8	741 0.3018 76.2	482 0.1963 49.5
17 0.0069 2.5	— — —	192 0.0784 28.8	475 0.1940 71.2	466 0.1903 69.9
— — —	25 0.0102 3.5	— — —	— — —	— — —
— — —	12 0.0049 1.3	273 0.1115 29.9	639 0.2610 70.1	455 0.1858 49.9
— — —	25 0.0102 2.9	228 0.0929 26.7	626 0.2550 73.3	512 0.2085 59.9
13 0.0053 1.3	— — —	324 0.1323 31.9	691 0.2822 68.1	486 0.1985 47.9
28.0 — —	— — —	259.8 0.1060 29.0	635.3 0.2593 71.0	480.5 0.1961 53.7

Table 6 Water circulation balance in hydrogeologic structure of Žihlavník-Baské limestone-dolomite

Hydrological year XI—X.	Dimension	Z precipitation	O_s runoff total	O_{pz} runoff underground (by springs)	Total runoff on hydrological years boundary $m^3 . s^{-1}$
1955	mm $m^3 . s^{-1}$ %	1129.7 1.0611 100.0	333.9 0.3136 29.6	333.9 0.3136 29.6	0.129
1956	mm $m^3 . s^{-1}$ %	1083.1 1.0145 100.0	315.0 0.2951 29.1	315.0 0.2951 29.1	0.4137
1957	mm $m^3 . s^{-1}$ %	1083.3 1.0175 100.0	368.5 0.3461 34.0	368.5 0.3461 34.0	0.2008
1958	mm $m^3 . s^{-1}$ %	1085.6 1.0196 100.0	408.3 0.3835 37.6	408.3 0.3835 37.6	0.1473
1959	mm $m^3 . s^{-1}$ %	762.1 0.7158 100.0	395.0 0.3710 51.8	395.0 0.3710 51.8	0.3474
1960	mm $m^3 . s^{-1}$ %	1077.0 1.0088 100.0	304.8 0.2855 28.3	304.8 0.2855 28.3	0.1837
1961	mm $m^3 . s^{-1}$ %	956.4 0.8983 100.0	435.0 0.4086 45.5	435.0 0.4086 45.5	0.3074
1962	mm $m^3 . s^{-1}$ %	1028.0 0.9655 100.0	470.9 0.4423 45.8	470.9 0.4423 45.8	0.2359
1963	mm $m^3 . s^{-1}$ %	1138.5 1.0693 100.0	367.7 0.3454 32.3	367.7 0.3454 32.3	0.1949
1964	mm $m^3 . s^{-1}$ %	851.4 0.7975 100.0	276.0 0.2585 32.4	276.0 0.2585 32.4	0.3017
1965	mm $m^3 . s^{-1}$ %	1175.2 1.1038 100.0	505.5 0.4748 43.0	505.5 0.4748 43.0	0.2463
Average 1955—1965	mm $m^3 . s^{-1}$ %	1033.7 0.9702 100.0	380.1 0.3568 36.8	380.1 0.3568 36.8	0.2639 —

block in Strážovské vrchy Mts. Hydrological years 1955—1965 (Area: 29.62 sq km, average altitude 625 m)

−R	+R	O_z	E_b	V_{BZ}
changing groundwater reserves in hydrostructure		effective reserves	evapotranspiration calculated from balance equations	evaporation from soil surface (by Budyko-Zubenokova method)
depletion of reserves from preceding years	transfer of reserves to following years			
— — —	57.6 0.0541 5.1	391.5 0.3677 34.7	738.2 0.6934 65.3	457.5 0.4297 40.5
30.9 0.0289 2.9	— — —	284.1 0.2661 26.2	799.0 0.7484 73.8	444.0 0.4170 41.0
20.0 0.0188 1.8	— — —	348.5 0.3273 32.2	734.8 0.6902 67.8	461.7 0.4336 42.6
— — —	46.4 0.0436 4.3	454.7 0.4271 41.9	630.9 0.5926 58.1	497.7 0.4662 45.8
32.8 0.0308 4.3	— — —	362.2 0.3402 47.5	399.9 0.3756 52.5	529.5 0.4973 69.5
— — —	28.0 0.0262 2.6	332.8 0.3117 30.9	744.2 0.6971 69.1	481.5 0.4522 44.7
12.4 0.0116 1.3	— — —	422.6 0.3969 44.2	533.8 0.5014 55.8	465.0 0.4367 48.6
11.5 0.0108 1.1	— — —	459.4 0.4315 44.7	568.6 0.5341 55.3	417.1 0.3907 40.6
— — —	23.1 0.0217 2.0	390.8 0.3671 34.3	747.7 0.7023 65.7	444.1 0.4171 39.0
6.8 0.0064 0.8	— — —	269.2 0.2522 31.6	582.2 0.5453 68.4	534.3 0.5018 62.8
— — —	1.2 0.0011 0.1	506.7 0.4759 43.1	668.5 0.6279 56.9	554.0 0.5203 47.1
— — —	41.9 — —	383.9 0.3603 37.1	649.8 0.6098 62.9	480.6 0.4512 46.5

Table 7 Balance of water circulation in hydrogeologic structure of limestones and dolomites of Harmanec

Hydrological year XI—X.	Dimension	Z	O_s	O_{pz}		O_p	Total runoff on hydrol. years boundary $m^3 . s^{-1}$
				runoff			
		precipitation	total	by springs	by surface streams	surficial	
1971	mm	1161.6	540.1	343.3	149.2	47.6	0.399
	$m^3 . s^{-1}$	1.0277	0.4778	0.3037	0.1320	0.0421	
	%	100.0	46.5	29.6	12.8	4.1	0.401
1972	mm	996.0	550.3	355.7	171.7	22.9	
	$m^3 . s^{-1}$	0.8796	0.4856	0.3139	0.1515	0.0202	
	%	100.0	55.2	35.7	17.2	2.3	0.451
1973	mm	768.8	412.6	329.9	76.3	6.4	
	$m^3 . s^{-1}$	0.6802	0.3651	0.2919	0.0675	0.0057	
	%	100.0	53.7	42.9	9.9	0.8	0.308
1974	mm	1450.2	453.0	327.4	95.7	29.9	
	$m^3 . s^{-1}$	1.2830	0.4008	0.2897	0.0847	0.0265	
	%	100.0	31.2	22.6	6.6	2.1	0.779
1975	mm	1323.0	710.1	457.9	225.2	27.0	
	$m^3 . s^{-1}$	1.1705	0.6282	0.4051	0.1992	0.0239	
	%	100.0	53.7	34.6	17.0	2.0	0.482
1976	mm	1092.4	513.4	371.4	120.8	21.2	
	$m^3 . s^{-1}$	0.9638	0.4530	0.3277	0.1066	0.0187	
	%	100.0	47.0	34.0	11.1	1.9	0.507
1977	mm	1354.3	764.5	492.2	239.1	33.2	
	$m^3 . s^{-1}$	1.1982	0.6764	0.4355	0.2115	0.0294	
	%	100.0	56.4	36.3	17.7	2.4	0.561
1978	mm	1124.2	623.0	447.5	148.6	26.9	
	$m^3 . s^{-1}$	0.9946	0.5512	0.3957	0.1315	0.0238	
	%	100.0	55.4	39.8	13.2	2.4	0.429
1979	mm	1082.1	525.6	372.9	135.6	17.1	
	$m^3 . s^{-1}$	0.9573	0.465	0.3299	0.1200	0.0151	
	%	100.0	48.6	34.5	12.5	1.6	0.393
1980	mm	1449.1	561.2	396.3	128.9	36.0	
	$m^3 . s^{-1}$	1.2785	0.4951	0.3496	0.1137	0.0318	
	%	100.0	38.7	27.3	8.9	2.5	0.552
Average 1971—1980	mm	1180.3	565.4	389.5	149.1	26.8	—
	$m^3 . s^{-1}$	1.0433	0.4998	0.3443	0.1318	0.0237	—
	%	100.0	47.9	33.0	12.6	2.3	—

syncline in Veľká Fatra Mts. Hydrologic years 1971—1980 (Area: 27.9 sq km, average altitude 963 m)

−R	+R	O_z	E_b	V_{BZ}
changing groundwater reserves in hydrogeologic structures		effective precipitation	evapotranspiration (calculated from balance equation)	evaporation from soil surface (by Budyko-Zubenokova method)
depletion of reserves of preceding years	transfer of reserves to following years			
— — —	0.9 0.0007 0.1	541.0 0.4786 46.6	620.6 0.5490 53.4	430.1 0.3805 37.0
— — —	24.4 0.0215 2.4	574.7 0.5070 57.6	422.3 0.3726 42.4	398.7 0.3518 40.0
88.3 0.0781 11.5	— — —	324.3 0.2869 42.2	444.5 0.3933 57.8	415.3 0.3674 54.0
— — —	152.4 0.1348 10.5	605.4 0.5356 41.7	844.8 0.7474 58.3	417.1 0.3689 28.8
51.6 0.0457 3.9	— — —	658.5 0.5826 49.8	664.5 0.5879 50.2	436.9 0.3865 33.0
— — —	18.5 0.0163 1.7	531.9 0.4693 48.7	560.5 0.4945 51.3	444.7 0.3924 40.7
— — —	8.2 0.0725 0.6	772.7 0.6836 57.1	581.6 0.5145 42.9	485.6 0.4296 35.9
44.9 0.0397 4.0	— — —	578.1 0.5114 51.4	546.1 0.4831 48.6	345.0 0.3052 30.7
20.7 0.0183 1.9	— — —	504.9 0.4467 46.7	577.2 0.5107 53.3	474.6 0.4199 43.9
— — —	63.7 0.0562 4.4	624.9 0.5513 43.1	824.2 0.7272 56.9	375.6 0.3402 26.6
— — —	62.6 — —	571.6 0.5053 48.4	608.6 0.5380 51.6	423.4 0.3743 35.9

Table 8 Water circulation balance in hydrogeologic structure of Muráň plateau limestones. Hydrological

Hydrological year XI—X.	Dimension	Z	O_s	O_{pz}				O_p
			runoff					
		precipitation	total	in continuously measured springs	in measured straight groundwater inflow to surface streams	excluded from hydrogr. surface streams	total underground runoff	surface
1971	mm $m^3.s^{-1}$ %	847.5 3.3896 100.0	425.3 1.7010 50.3	285.3 1.1412 33.7	70.9 0.2837 8.4	55.5 0.2220 6.5	411.7 1.6469 48.6	13.6 0.0542 1.6
1972	mm $m^3.s^{-1}$ %	1082.7 4.3184 100.0	408.5 1.6295 37.7	252.4 1.0067 23.3	95.3 0.3802 8.8	44.4 0.1770 4.1	392.1 1.5639 36.2	16.4 0.0656 1.5
1973	mm $m^3.s^{-1}$ %	697.4 2.7893 100.0	225.7 0.9025 32.4	157.3 0.6292 22.6	34.7 0.1387 5.0	29.3 0.1170 4.2	221.3 0.8849 31.7	4.4 0.0176 0.6
1974	mm $m^3.s^{-1}$ %	1265.2 5.0601 100.0	534.6 2.1379 42.3	352.7 1.4107 27.9	95.6 0.3823 7.6	50.3 0.2010 4.0	498.6 1.9940 39.4	36.0 0.1439 2.8
1975	mm $m^3.s^{-1}$ %	1103.6 4.4138 100.0	547.6 2.1900 49.6	347.6 1.3902 31.5	126.7 0.5066 11.5	61.6 0.2460 5.6	535.8 2.1428 48.6	11.8 0.0472 1.1
1976	mm $m^3.s^{-1}$ %	900.6 3.5919 100.0	333.1 1.3285 37.0	223.5 0.8914 24.8	59.6 0.2376 6.6	35.4 0.1410 3.9	318.4 1.2700 35.4	14.7 0.0585 1.6
1977	mm $m^3.s^{-1}$ %	1081.3 4.3245 100.0	686.3 2.7448 63.5	446.8 1.7869 41.3	135.5 0.5418 12.5	72.1 0.2885 6.7	654.4 2.6172 60.5	31.9 0.1277 3.0
1978	mm $m^3.s^{-1}$ %	986.0 3.9433 100.0	524.7 2.0984 53.2	319.4 1.2776 32.4	133.6 0.5345 13.5	49.7 0.1988 5.0	502.8 2.0109 51.0	21.9 0.0874 2.2
1979	mm $m^3.s^{-1}$ %	923.5 3.6936 100.0	469.7 1.8786 50.9	299.7 1.1987 32.5	111.6 0.4463 12.1	36.5 0.1458 4.0	447.8 1.7908 48.5	22.0 0.0878 2.4
1980	mm $m^3.s^{-1}$ %	1184.8 4.7255 100.0	615.3 2.4542 51.9	404.2 1.6121 34.1	119.8 0.4777 10.1	80.0 0.3189 6.8	603.9 2.4087 51.0	11.4 0.0454 0.9
Average 1971—1980	mm $m^3.s^{-1}$ %	1007.3 4.0253 100.0	477.1 1.9065 47.3	308.9 1.2344 30.6	98.3 0.3928 9.8	51.5 0.2058 5.1	458.7 1.8330 45.5	18.4 0.0735 1.8

years 1971—1980 (Area: 126.125 sq km, average altitude 997 m)

Total runoff on hydrol. years boundary ($m^3 . s^{-1}$)	$-R$	$+R$	O_z	E_b	V_{BZ}
	changing groundwater reserves in hydrogeologic structure		effective precipitation	evapotranspiration (calculated from balance equation)	evaporation from soil surface (by Budyko-Zubenokova method)
	depletion of reserves of preceding years	transfer of reserves to following years			
0.4802 0.4686	0.4 0.0014 0.0	— — —	424.9 1.6997 50.1	422.6 1.6900 49.9	456.5 1.8267 53.9
   0.5377	— — —	2.1 0.0085 0.2	410.6 1.5380 37.9	672.1 2.6804 62.1	441.2 1.7600 40.8
   0.3580	5.6 0.0222 0.8	— — —	220.1 0.8803 31.6	477.3 1.9090 68.4	471.9 1.8874 67.7
   4.6787	— — —	43.4 0.1736 3.4	578.0 2.3115 45.7	687.2 2.7486 54.3	438.1 1.7520 34.6
   1.2931	22.9 0.0915 2.1	— — —	524.7 2.0985 47.5	578.9 2.3153 52.5	543.6 2.1742 49.3
   4.5474	— — —	21.8 0.0869 2.4	354.9 1.4154 39.4	545.7 2.1765 60.6	468.2 1.8675 52.0
   0.5158	37.4 0.1497 3.5	— — —	648.9 2.5951 60.0	432.4 1.7294 40.0	449.6 1.7981 41.6
   0.4294	2.7 0.0107 0.3	— — —	522.0 2.0877 52.9	464.0 1.8556 47.1	463.0 1.8516 47.0
   0.5226	— — —	2.9 0.0115 0.3	472.6 1.8901 51.2	450.9 1.8035 48.8	441.8 1.7670 47.8
   1.8527	— — —	22.1 0.0879 1.9	637.4 2.5421 53.8	547.4 2.1834 46.2	378.8 1.5108 32.0
— — —	— — —	23.3 — —	479.4 1.9157 47.6	527.9 2.1095 52.4	455.3 1.8194 45.2

Table 9 Water circulation balance in hydrogeologic structure of limestones and dolomites of Veľký Choč

Hydrological year XI—X.	Dimension	Z	O_s	O_{pz}		O_p
			runoff			
				underground		
		precipitation	total	by springs	by surface streams	surficial
1971	mm	335.1	560.1	154.8	380.4	25.0
	$m^3 . s^{-1}$	0.5767	0.3455	0.0955	0.2346	0.0154
	%	100.0	59.9	16.6	40.7	2.7
1972	mm	1106.8	494.1	142.8	293.3	58.0
	$m^3 . s^{-1}$	0.6808	0.3039	0.0878	0.1804	0.0357
	%	100.0	44.6	12.9	26.5	5.2
1973	mm	760.0	375.2	150.3	211.8	13.1
	$m^3 . s^{-1}$	0.4687	0.2314	0.0927	0.1306	0.0081
	%	100.0	49.4	19.8	27.9	1.7
1974	mm	1285.6	475.2	142.5	265.4	67.3
	$m^3 . s^{-1}$	0.7929	0.2931	0.0879	0.1637	0.0415
	%	100.0	37.0	11.1	20.6	5.2
1975	mm	1035.1	500.1	162.8	318.9	18.3
	$m^3 . s^{-1}$	0.6384	0.3084	0.1004	0.1967	0.0113
	%	100.0	48.3	15.7	30.8	1.8
1976	mm	928.6	566.9	166.8	355.9	44.2
	$m^3 . s^{-1}$	0.5712	0.3487	0.1026	0.2189	0.0272
	%	100.0	51.0	18.0	38.3	4.8
1977	mm	950.7	533.4	185.8	319.4	28.2
	$m^3 . s^{-1}$	0.5863	0.3290	0.1146	0.1970	0.0174
	%	100.0	56.1	19.5	33.6	3.0
1978	mm	841.7	448.9	176.3	246.1	26.4
	$m^3 . s^{-1}$	0.5191	0.2768	0.1087	0.1518	0.0163
	%	100.0	53.3	20.9	29.2	3.1
1979	mm	902.0	383.6	172.2	192.3	19.0
	$m^3 . s^{-1}$	0.5563	0.2366	0.1062	0.1186	0.0117
	%	100.0	42.5	19.1	21.3	2.1
1980	mm	1020.8	412.2	162.6	220.8	28.9
	$m^3 . s^{-1}$	0.6279	0.2536	0.1000	0.1358	0.0178
	%	100.0	40.4	15.9	21.6	2.8
Average 1971—1980	mm	976.6	475.1	161.7	280.4	33.1
	$m^3 . s^{-1}$	0.6018	0.2927	0.0996	0.1728	0.0202
	%	100.0	48.7	16.6	28.7	3.4

block in Chočské vrchy Mts. Hydrological years 1971—1980 (Area: 19.45 sq km, average altitude 1096 m)

Total runoff on hydrol. years boundary ($m^3 . s^{-1}$)	$-R$	$+R$	O_z	E_h	V_{BZ}
	changing groundwater reserves in hydrogeologic structure		effective precipitation	evapotranspiration (calculated from balance equation)	evaporation from soil surface (by Budyko-Zubenokova method)
	depletion of reserves of preceding years	transfer of reserves to following years			
0.2999	13.9 0.0086 1.5	— — —	546.2 0.3369 58.4	388.9 0.2399 41.6	453.3 0.2796 48.5
0.2565	4.4 0.0027 0.4	— — —	489.7 0.3012 44.2	617.1 0.3796 55.8	449.5 0.2765 40.6
0.2429	20.8 0.0128 2.7	— — —	354.4 0.2186 46.6	405.6 0.2502 53.4	435.6 0.2687 57.3
0.1779	— — —	47.6 0.0294 3.7	522.8 0.3224 40.7	762.8 0.4705 59.3	474.3 0.2925 36.9
0.4414	2.6 0.0016 0.3	— — —	497.5 0.3068 48.1	537.6 0.3316 51.9	484.7 0.2989 46.8
0.3547	— — —	1.3 0.0008 0.1	568.2 0.3495 61.2	360.4 0.2217 38.8	482.7 0.2969 52.0
0.4334	33.6 0.0207 3.5	— — —	499.8 0.3083 52.6	450.9 0.2781 47.4	406.6 0.2508 42.8
0.2174	— — —	3.6 0.0022 0.4	452.5 0.2791 53.8	389.2 0.2400 46.2	396.9 0.2448 47.2
0.2287	8.4 0.0052 0.9	— — —	375.2 0.2314 41.6	526.8 0.3249 58.4	459.2 0.2832 50.9
0.2025	— — —	30.4 0.0187 3.0	442.6 0.2722 43.4	578.2 0.3556 56.6	388.1 0.2387 38.0
0.2974 — — —	0.8 — —	— — —	474.9 0.2926 48.6	501.6 0.3092 51.4	443.1 0.2732 45.4

is 8.43 $l.s^{-1}.km^{-2}$. In higher situated hydrogeologic structures with increasing total precipitation and decreasing temperatures the groundwater specific runoff increases. In hydrologic structure Žihlavník-Baské (625 m above sea level) it is 12.04 $l.s^{-1}.km^{-2}$, and in high situated structures (963—1096 m above sea level) it even increases to 15.05—17.92 $l.s^{-1}.km^{-2}$ (of which the groundwater specific runoff is 14.01—17.07 $l.s^{-1}.km^{-2}$).

Increasing total precipitation and decreasing temperatures with growing altitude affect remarkably the value of ground-water specific runoff. There are further factors (accumulation ability of the structure, morphology, afforestation degree, a. o.) causing significant deviations from the basical relation as obvious in three high-situated hydrogeologic structures.

Fissure-karst hydrogeologic structures with the type of their structure, different lithologic character (different types of limestones, different limestone, dolomite ratio), different character and degree of deformation, different permeability represent different conditions for groundwater accumulation and for regulation ability of the structure in respect of groundwater runoff.

Table 10 Specific runoff from evaluated closed hydrogeologic structures

Hydrological year (XI—X)	Hydrogeologic structure of SW part of Krížna nappe in Pezinské Karpaty Mts. specific runoff in $l.s^{-1}.km^{-2}$			Hydrogeologic structure Žihlavník-Baské specific runoff in $l.s^{-1}.km^{-2}$		
	total	underground	surficial	total	underground	surficial
1955	—	—	—	10.59	10.59	—
1956	—	—	—	9.96	9.96	—
1957	9.95	9.95	—	11.68	11.68	—
1958	8.78	8.78	—	12.95	12.95	—
1959	8.75	8.75	—	12.53	12.53	—
1960	7.93	7.93	—	9.64	9.64	—
1961	6.63	6.63	—	13.79	13.79	—
1962	non evaluated - interrupted measurements			14.93	14.93	—
1963	8.28	8.28	—	11.66	11.66	—
1964	6.42	6.42	—	8.73	8.73	—
1965	10.68	10.68	—	16.03	16.03	—
$\bar{x}$	8.43	8.43	—	12.04	12.04	—
$\frac{max}{min}$	1.66	1.66	—	1.84	1.84	—

The existing data show that the fissure-karst hydrostructures mainly control differences in groundwater specific runoff between single hydrological years. Whereas in hydrogeologic structures with a great accumulation and a good regulation ability in the evaluated periods the ratio of the maximum and the minimum annual specific runoff varies from 1.51 to 1.85, in hydrostructures with low accumulation ability (extensive karst — the Muráň plateau) the ratio is 3.04.

Table 11 Specific runoff from evaluated closed hydrogeologic structures

Hydrol. year (XI—X)	Hydrogeologic structure of Harmanec syncline average annual spec. runoff $l.s^{-1}.km^{-2}$			Hydrogeologic structure of Muráň plateau, average annual specific runoff $l.s^{-1}.km^{-2}$			Hydrogeologic structure of Veľký Choč block, average annual specific runoff $l.s^{-1}.km^{-2}$		
	total	under-ground	surficial	total	under-ground	surficial	total	under-ground	surficial
1971	17.13	15.62	1.51	13.49	13.06	0.43	17.76	16.97	0.79
1972	17.41	16.68	0.73	12.92	12.40	0.52	15.62	13.79	1.83
1973	13.09	12.88	0.21	7.16	7.02	0.14	11.90	11.48	0.42
1974	14.37	13.42	0.95	16.95	15.81	1.14	15.07	12.94	2.13
1975	22.52	21.66	0.86	17.36	16.99	0.37	15.86	15.28	0.58
1976	16.24	15.57	0.67	10.53	10.07	0.46	17.93	16.53	1,40
1977	24.24	23.19	1.05	21.76	20.75	1.01	16.92	16.02	0.90
1978	19.76	18.90	0.86	16.64	15.95	0.69	14.23	13.39	0.84
1979	16.67	16.13	0.54	14.90	14.20	0.70	12.16	11.56	0.60
1980	17.75	16.61	1.14	19.46	19.10	0.36	13.04	12.12	0.92
1971—1980	17.92	17.07	0.85	15.12	14.54	0.58	16.05	14.01	1.04
$\frac{max}{min}$	1.85	1.80	7.19	3.04	2.96	8.14	1.51	1.48	5.07

Relations between precipitation and effective precipitation in representative hydrogeologic structures

The purpose of hydrologic balance is evaluation of precipitation — runoff relations in fissure-karst hydrostructures on the basis of data on representative hydrogeologic structures. The relations in single hydrostructure and differences of relations between hydrostructures of various character in areas of different climate were examined.

Generally there is a weak correlation between annual total precipitation and annual runoff in single hydrological years.

Besides other influences and possible errors in measurements (mainly in Žihlavník-Baské hydrostructure), tke relations are affected by changing groundwater reserves in hydrogeologic structures. The evaluation of changing groundwater reserves during hydrological years and inclusion of the resulting values into the solution proved better correlation. Considering the changing groundwater reserves and their transfer from one hydrological year to another, we passed from the evaluation of the precipitation/runoff ratio to the evaluation of the precipitation/effective precipitation (precipitation runoff in evaluated hydrological year — Oz) ratio.

Good correlations with correlation coefficient 0.781, 0.812, 0.827 were found in three structures, weaker correlations were found in the Žihlavník-Baské hydrostructure (0.392) and in the Veľký Choč hydrostructure (0.492). In this structure it is due to impossible accurate determination of groundwater reserves changes owing to intense exploitation (recorded monthly by water-meters enabling though accurate annual balance evaluation but inaccurate evaluation of changing groundwater reserves in a hydrostructure), whereas in the Žihlavník-Baské structure the cause of the dispersion is not clear. It may be due to less exact (weekly) systematical measurements on springs. In all hydrostructures the effective precipitation increases — although with certain deviations — with increasing precipitation in single years.

The relations in the Krížna nappe hydrostructure in the Pezinské Karpaty Mts. and in the Muráň plateau hydrostructure are presented in Figures 3 and 4. The relations in other structures are given in Tables 6, 7, 9.

Differences between hydrostructures concerning the precipitation/effective precipitation ratio were paid a particular attention. The differences are documented by Fig. 5 summarizing data on the precipitation/effective precipitation ratio in all five hydrostructures. Fig. 5 shows increase of effective precipitation with increasing total precipitation controlled by the structure altitude (the influence of decreasing evapotranspiration in higher-situated hydrogeologic structures). For example: in the case of 1000 mm precipitation in a low-situated structure (Krížna nappe in Malé Karpaty Mts., altitude 550 m) effective precipitation represents only 28 % of total annual precipitation, whereas in high-situated hydrogeologic structures (Harmanec syncline, Muráň plateau, Veľký

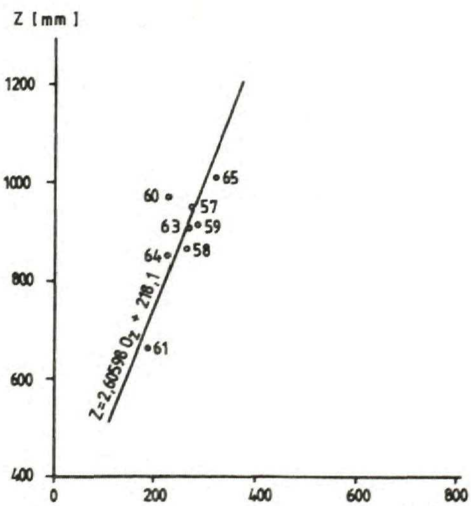

Fig. 3 Relation between precipitation (Z) and effective precipitation (O_z) in Krížna nappe hydrostructure in Pezinské Karpaty Mts. in hydrological years 1957—1965

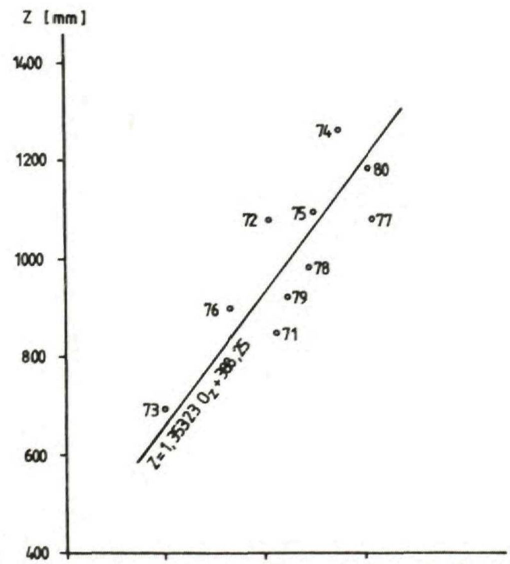

Fig. 4 Relation between precipitation (Z) and effective precipitation (O_z) in hydrogeologic structure of Muráň plateau in hydrological years 1971—1980.

Choč block — altitude 963—1096 m) effective precipitation ranges to 47 % of total annual precipitation. Character of hydrogeologic structures also influences considerably the relation between precipitation and effective precipitation. It is best seen in the Muráň plateau hydrostructure. In contrast to others it has the character of a plain and consists mostly of limestones on the surface. The precipitation/effective precipitation ratio is different. When annual precipitation

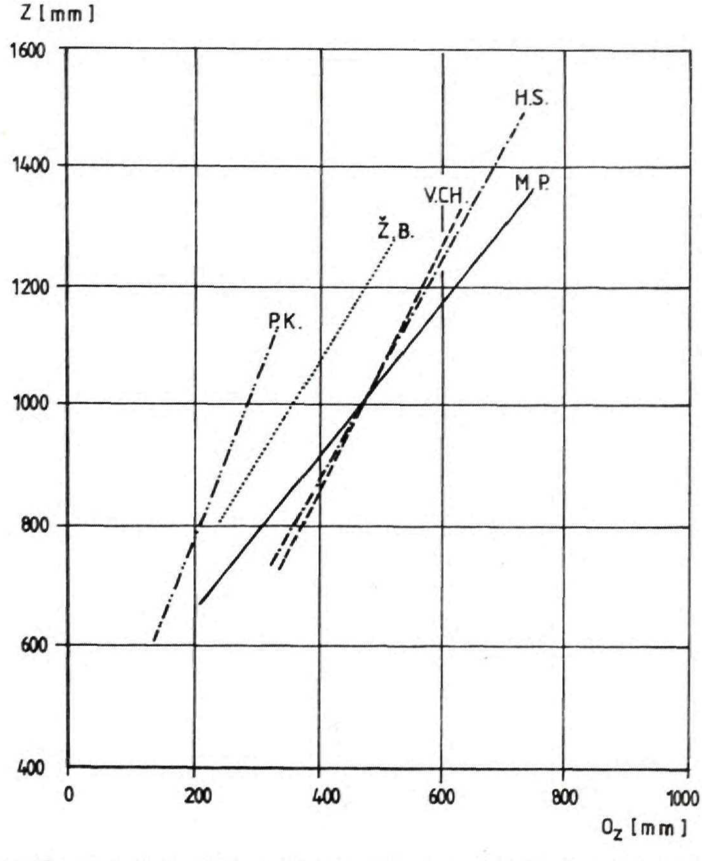

Fig. 5 Differences in precipitation (Z) effective precipitation ratio (O_z) between single hydrostructures evaluated. Hydrogeologic structures and their average altitudes: P. K. — Krížna nappe in Pezinské Karpaty Mts. (507 m), Ž. B. — Žihlavník-Baské (625 m), H. S. — Harmanec syncline (963 m), V. CH. — Veľký Choč (1096 m).

is low, effective precipitation is lower than in other structures. At high precipitation the effective precipitation is higher as well. No unambiguous explanation is possible because of limited number of structures studied. I suppose that evapotranspiration at lower precipitation increases and is due to overheating of exposed carbonates of the plain. I also expect more favourable and rapid precipitation water infiltration into horizontal karstified carbonates at high total precipitation. A comparison to other structures (with the exception of Žihlavník-Baské representing a transitional type of structure) shows that hydrogeologic conditions of precipitation water infiltration to the structure are more favourable than in other structures owing to its horizontal position and opening by karstification.

Changes of groundwater reserves in evaluated hydrogeologic structures

The evaluation of groundwater reserves changes in hydrogeologic structures should precise the hydrological balance and enable calculation of effective precipitation to reveal groundwater reserves changes in time and accumulation abilities of lithologically and tectonically different structures composed of carbonate rocks.

Groundwater reserves changes in representative closed hydrogeologic structures were calculated for single hydrological years by the method mentioned in the preceding parts of this work.

Hydrogeologic structures were evaluated in respect of groundwater reserves changes in two periods. Two structures were evaluated in hydrological years 1957—1965 and/or 1955—1965, three structures in 1971—1980. The results are given in tables of hydrological balances (Tab. 5—9). A significant groundwater reserves depletion was recorded in a part of the Krížna nappe (Pezinské Karpaty Mts.) in the hydrostructure of limestones and dolomites, evaluated in hydrological years 1957—1965 (beginning on Nov. 1, 1956). Since 1957 to 1961 (5 hydrological years) groundwater reserves accumulated in the structure before the hydrological year 1957 did not participate in underground runoff only in 1959. Since 1962 the reserves had gradually (hydrological years 1962—1964) been recharged and in 1965 decreased again. The period 1957—1965 is deficit for this hydrogeologic structure. At the end of this period the groundwater reserves were deficient (28 mm = 360.640 m^3 of fissure-karst groundwater) in comparison with the beginning of the hydrologic year 1957. In accordance with hydrogeological conditions (plentiful dolomites with good accumulation abilities) the reserves changes prove good accumulation and compensation abilities of the underground runoff from the hydrogeologic structure. It was enabled by good recharge of underground runoff from the reserves in the period from Nov. 1, 1956 to October 30, 1961.

The processes of depletion and recharge in single hydrological years were markedly different in the limestone-dolomite block Žihlavník-Baské in practically the same period (1955—1965). Years of decreasing and increasing reserves and groundwater recharge alternated mainly in the period 1955 and 1958. Evaluation of the period 1955—1965 showed a significant increase in groundwater reserves (41.9 mm). A comparison with the evaluation period 1957—1965 concerning the preceding hydrostructure also showed increasing (15.2 mm) groundwater reserves. In spite of higher karstification the structure shows good accumulation — and compensation abilities.

A comparison of data on the two structures from the period 1957—1965 revealed considerable differences in groundwater reserves. The differences may partly be due to geologic differences between the structures but they are mostly caused by different effective precipitation in single hydrological years.

Three high-positioned fissure-karst hyrogeologic structures (Harmanec syncline — HS, Muráň plateau — MP, Veľký Choč — V. CH.) evaluated in the period 1971—1980 also show differences: the accumulation- and compensation abilities of the Harmanec syncline are much greater than shown by the Muráň plateau and Veľký Choč (Fig. 6, 7).

The differences are more obvious when groundwater reserves changes in the Harmanec syncline and in the Muráň plateau of approximately equal altitude are compared. These hydrostructures represent a classical example of two extreme hydrologeologic conditions for groundwater reserves formation in fissure-karst rock environment.

The Harmanec syncline hydrogeologic structure is characterized by extreme accumulation abilities and by the ability of underground runoff regulation. In hydrological years 1971 and 1972 no significant groundwater reserves changes took place (1971: +1 mm). In hydrological year 1972 the reserves were slightly recharged (+24.4 mm). In 1973 the total precipitation was extremely low (769 mm) and an extensive groundwater reserves depletion proceeded (−88 mm) enabling the underground runoff to be kept on a comparatively high level in this extremely dry year (total specific runoff 13.09 $l . s^{-1} . km^{-2}$, groundwater specific runoff 12.88 $l . s^{-1} . km^{-2}$). In comparison to the average specific runoff for the evaluated decade (17.91 $l . s^{-1} . km^{-2}$) it represents 73 per cent. The year 1974 represents another extreme. Total precipitation (1450 mm) and precipitation infiltration (19.19 $l . s^{-1} . km^{-2}$) were high in that year and the total specific runoff was very low (14.36 $l . s^{-1} . km^{-2}$). The difference 4.83 $l . s^{-1} . km^{-2}$ (+152,4 mm) was accumulated in the form of recharge of depleted reserves and formation of further reserves. Owing to these reserves the structure filling was kept in the period 1975—1977 in spite of a considerable depletion in 1975. In 1979 the groundwater reserves got to the level of year 1971. In 1980 the structure was again filled with groundwater (+63.7 mm) so from the evaluated decade 1971—1980 a substantial transfer of groundwater took place to the period after 1980 (Fig. 6, 7).

Situation is different in the Muráň plateau hydrostructure in the same decade (1971—1980). Because of intense karstification and rapid groundwater depletion the accumulation is very limited as well as compensation of groundwater runoff in the course of the evaluated decade. Fig. 7 shows that there was practically no recharge in hydrological years 1971—1972. In the extremely dry year 1973 (total annual precipitation 698 mm) only a slight depletion of groundwater proceeded (5.6 mm) since there were almost no reserves in the structure above the erosion level. A more significant reserves accumulation (+43 mm) took place in the extremely humid year 1974 (annual total precipitation 1265 mm).

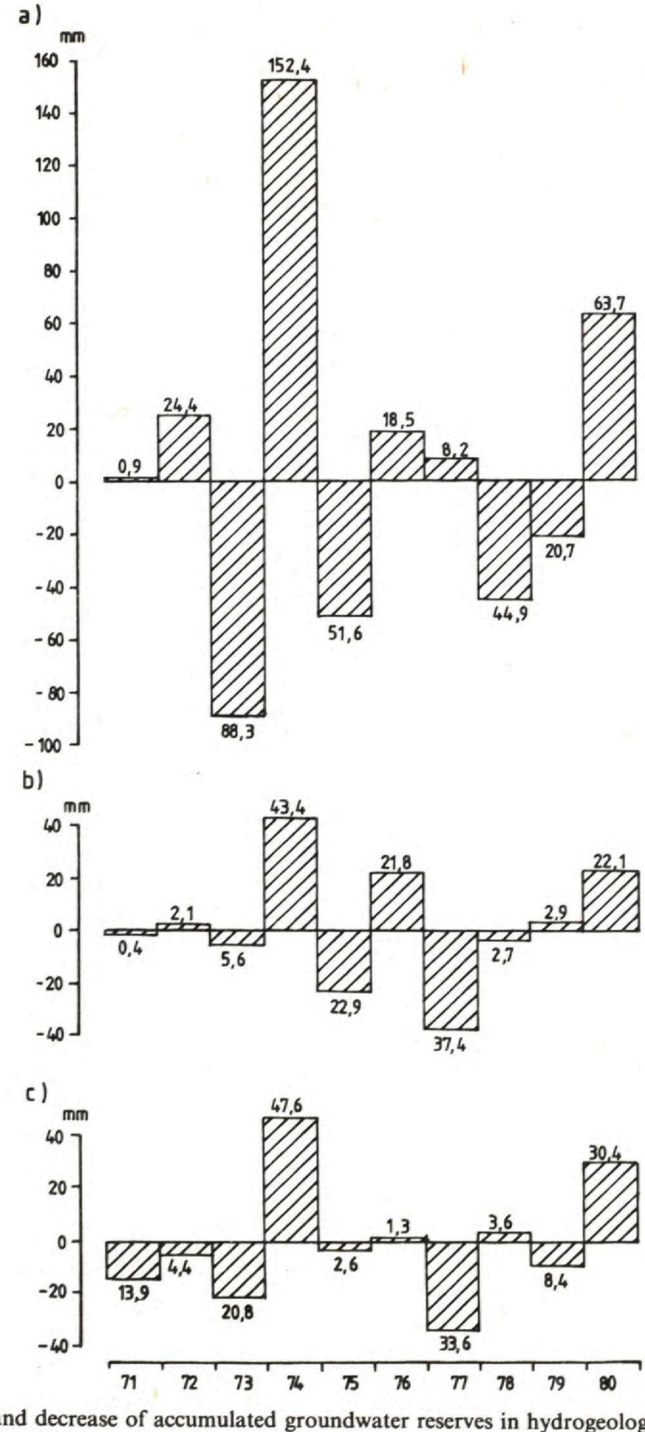

Fig. 6 Increase and decrease of accumulated groundwater reserves in hydrogeologic structures in hydrological years 1971—1980
a — Harmanec syncline hydrostructure in Veľká Fatra Mts., b — Muráň plateau hydrostructure, c — Veľký Choč hydrostructure in Chočské vrchy Mts.

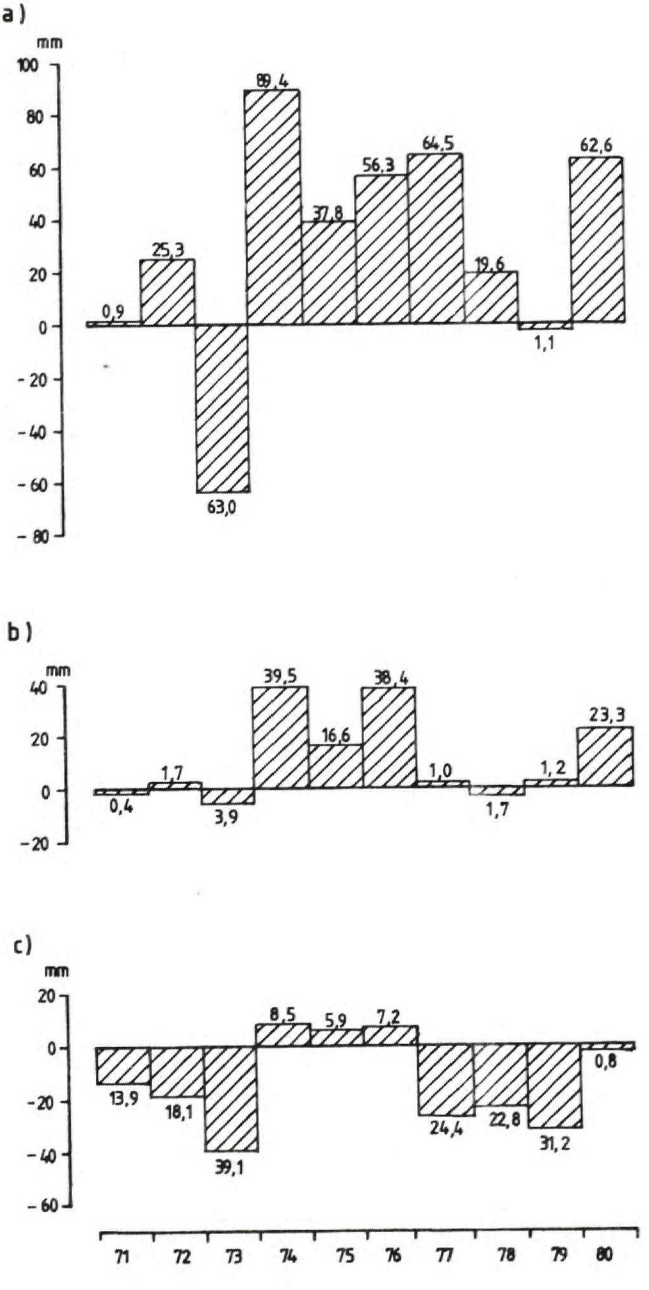

Fig. 7 Changes of groundwater reserves accumulation in hydrogeologic structures
a — hydrogeologic structure of Harmanec syncline in Veľká Fatra Mts., b — Muráň plateau hydrogeologic structure, c — Veľký Choč hydrogeologic structure in Chočské vrchy Mts.

The reserves (together with the recharge in 1976) enabled partial regulation of underground runoff in 1975 and 1977.

In hydrological years 1978 and 1979 the hydrostructure was depleted again like in 1971—1973, without groundwater reserves above erosion level. It was more (+22.1 mm) recharged in 1980. The recharge was followed by a slight groundwater reserves transfer from the period 1971—1980 to the period after 1980.

A comparison of the two hydrogeological structures of fissure-karst water shows different influence of groundwater reserves changes upon their general regime and upon their long provision of exploitable groundwater sources. The extremely dry year 1973 is a classical example. Owing to great accumulation ability of the Harmanec syncline hydrostructure and to extensive depletion of groundwater reserves the hydrostructure is significant for water economy (total average annual specific runoff 13.09 $l.s^{-1}.km^{-2}$, of which 2.8 $l.s^{-1}.km^{-2}$ — 21 % is from groundwater reserves).

The Muráň plateau structure with low accumulation ability only had 5.6 mm reserves above the erosion level at the beginning of 1973. Groundwater runoff was only recharged by precipitation infiltration of the evaluated hydrological year. Low total precipitation 697 mm representing 69 % in comparison to total average precipitation in the decade evaluated (1007 mm) caused a catastrophic situation reflected in the average annual specific runoff decreasing to 7.16 $l.s^{-1}.km^{-2}$ (underground runoff to 7.02 $l.s^{-1}.km^{-2}$) representing only 47 % of average specific runoff for the period 1971—1980.

The data on different groundwater reserves and their change in time prove great theoretical (precision of hydrological balances, calculation of effective precipitation) and practical (extent of runoff compensation, singificance of more exact information about groundwater reserves in fissure-karst hydrogeologic structures. The information may enable prognosis of extremely low underground runoff occurring in different hydrogeologic structures.

Evapotranspiration in fissure-karst hydrogeologic structures

Calculation of evapotranspiration is one of most serious problems in balance evaluation of water in fissure-karst hydrogeologic structures and in the determination of natural groundwater resources in the structures. Generally, hydrological balance is regarded as the most accurate method of evapotranspiration determination since in contrast to calculation methods it considers all factors controlling its formation. The evaluation of hydrological balances of five closed hydrogeological structures of fissure-karst water (discussed in detail in preceding chapters) in areas of different climate, evaluated in single hydrological years for 8—11 years represents an extensive basis for the approach to evapotranspiration in hydrogeologic environment of this type, and information about evapotranspiration concerning fissure-karst hydrogeologic structures in the West Carpathians at altitudes ranging from 500 to 1100 m.

In all five hydrostructures the determination of average annual evapotranspiration by hydrological balance results in higher values than those concerning evaporation from soil surface, calculated by Budyko-Zubenokova method. In ČSSR such values often replace evapotranspiration and are usually lower in single structures from 11.7 % to 30.4 % (Tab. 12; TOMLAIN 1980, 1986; TOMLAIN et al. 1972—81). Evapotranspiration determined by balance shows much greater variability than soil surface evaporation determined by Budyko-Zubenokova method (Tab. 5—9). The evaluation shows that the average annual evapotranspiration in single structures, proved by hydrological balance is controlled by altitude partly accounting different climatic conditions of single structures (Fig. 8). In the evaluation of more structures the relation $E = 769.5 - 0.2206\ H$ (Fig. 8) might be used for the determination of average values of evapotranspiration in fissure-karst hydrogeologic structures with intense afforestation, situated in altitudes between 500 and 1100 m.

Table 12 Average annual evapotranspiration E_b and average annual soil surface evaporation (E_{BZ}) in single hydrogeologic structures in hydrological years evaluated

Hydrogeologic structure, evaluated period of hydrological years	Average altitude of hydrogeol. structure m	Average precipitation mm	Evapotranspiration E_b mm	Soil surface evaporation E_{BZ} mm	Difference $E_b - E_{BZ}$ %
Veľký Choč 1971—1980	1096	977	502	443	11.7
Muráň plateau 1971—1980	997	1007	528	455	13.8
Harmanec syncline 1971—1980	963	1180	609	423	30.4
Žihlavník-Baské 1955—1965	625	1034	650	481	26.0
Krížna nappe of Malé Karpaty Mts. 1957—1965 (except 1962)	507	895	635	481	24.4

Table 13 Relationship between precipitation (Z) and evapotranspiration (E_b) expressed by linear correlation coefficient

Hydrogeologic structure	Evaluated period	Number of hydrologic years	Coefficient of linear correlation between annual precipitation and annual evapotranspiration
Veľký Choč	1971—80	10	0.89
Muráň plateau	1971—80	10	0.68
Harmanec syncline	1971—80	10	0.88
Žihlavník-Baské	1955—65	11	0.82
Krížna nappe of Malé Karpaty Mts.	1957—65 (except 1962)*	8	0.93

* In hydrological year 1962 systematic measurements of underground runoff were interrupted.

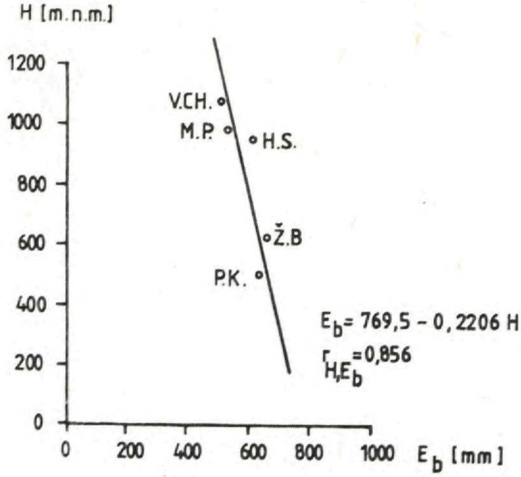

Fig. 8 Relation between average altitude (H) of hydrostructures evaluated and average evapotranspiration (E_b) in period evaluated

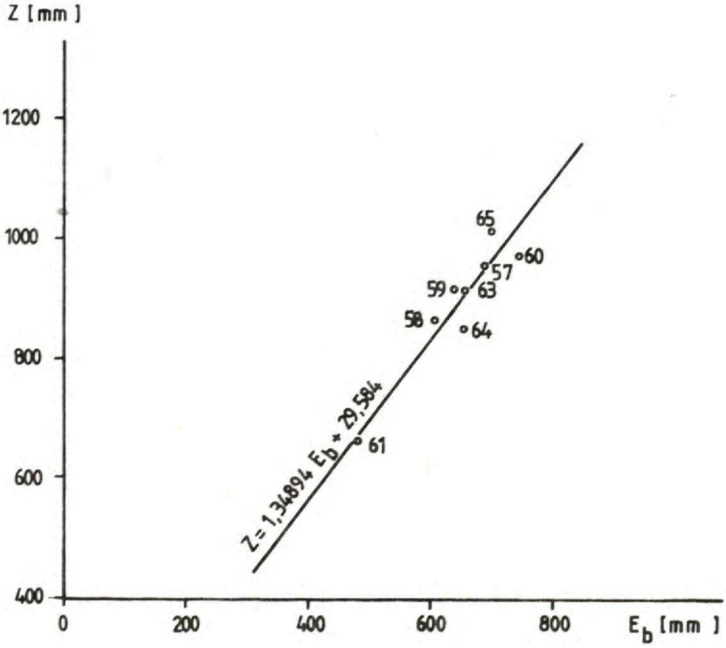

Fig. 9 Relation between precipitation (Z) and evapotranspiration (E_b) determined by hydrological balance equation in Krížna nappe hydrostructure of Pezinské Karpaty Mts. in 1957—1965.

Particular attention was paid to relationship between precipitation and evapotranspiration in hydrogeologic structures in single years. In all hydrostructures evaluated evapotranspiration was well controlled by total precipitation (Table 13). The results are given in Tables 5—9 and Fig. 9 and 10. Evapotranspiration was extremely high in hydrological years of extremely high total precipitation and in the period following extremely dry years. It is proved (see below) that evapotranspiration increases in afforested areas, so it is logical that evapotranspiration values are high in the years of high precipitation. We must, however, admit that the extremely high evapotranspiration in periods following extremely dry years (e. g. 1974 in the three then evaluated structures) may partly be accompanied with water preservation in dried soil pack and with groundwater accumulation in biomass (mainly in wood plants) after the dry season.

Fig. 11 shows a comparison between annual total precipitation and annual evapotranspiration in single hydrostructures evaluated. Fig. 11 shows higher evapotranspiration from precipitation in hydrogeologic structures of smaller altitudes owing to higher temperatures (Krížna nappe in Pezinské Karpaty Mts.,

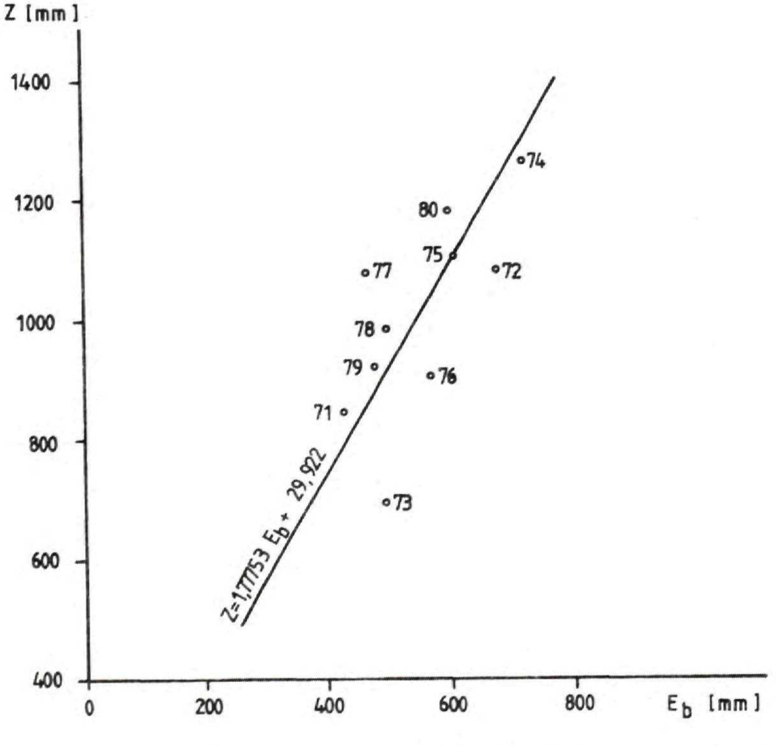

Fig. 10 Relation between precipitation (Z) and evapotranspiration (E_b) determined by hydrological balance equation in hydrostructure of Muráň plateau in 1971—1980.

Žihlavník-Baské) than in high altitude hydrostructures (Muráň plateau, Harmanec syncline, Veľký Choč block).

Evapotranspiration in single closed hydrostructures, proved by the balance method has higher values in average than total evaporation from soil surface in equal hydrogeologic structures calculated by the Budyko-Zubenokova method. The comparison was used because this is the most exact method.

The difference is 21 % in average from all the structures evaluated. It is greater (24—26 %) in structures of lower altitudes in contrast to higher situated structures (12—14 %) with the exception of the Harmanec syncline hydrostructure where the difference ranges up to 30.4 % (Tab. 12) in spite of its greater altitude.

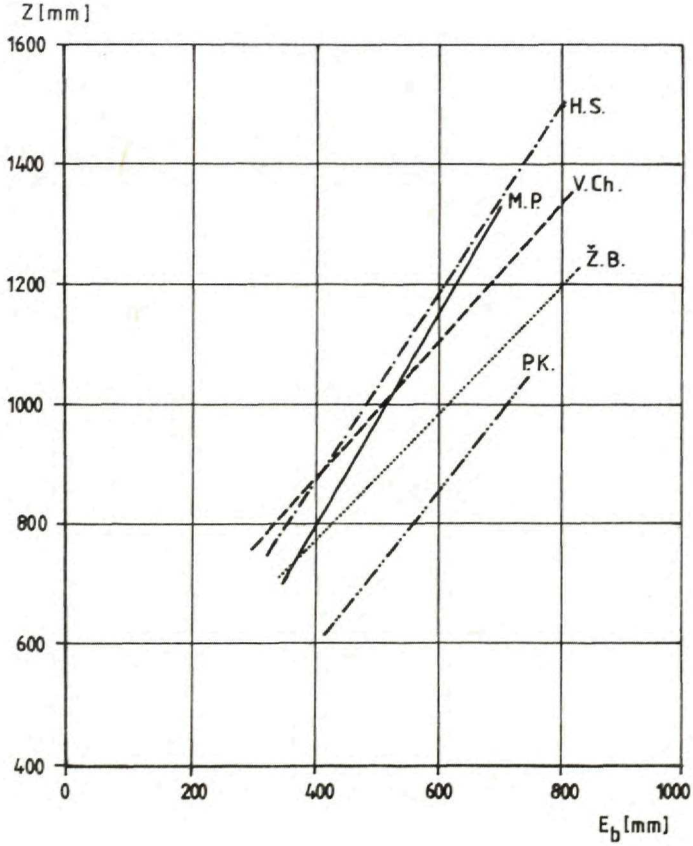

Fig. 11 Differences in precipitation (Z)/evapotranspiration (E_b) ratio between single hydrostructures evaluated

Hydrogeologic structures and their average altitudes: P. K. — Krížna nappe in Pezinské Karpaty Mts. (507 m), Ž. B. — Žihlavník-Baské (625 m), H. S. — Harmanec syncline (963 m), M. P. — Muráň plateau (997 m), V. CH. — Veľký Choč (1096 m).

Although some inaccuracy of single terms of the balance equation overvaluating the balance-calculated evapotranspiration should be admitted (mainly as regards runoff and groundwater reserves change, because precipitation is rather undervaluated) still the loading of balances with extensive concordant errors in all five structures measured and balance evaluated separately in single hydrological years, can be excluded. This is why I agree with the opinion that the data concerning substantially higher evapotranspiration in fissure-karst hydrogeologic structures than assumed before in the West Carpathian areas evaluated, are proved as reliable.

Discussion

The results of hydrological balances in fissure-karst hydrogeologic structure of the West Carpathians prove much higher evapotranspiration than the results of formerly used calculation methods. In contrast to the Budyko-Zubenokova method evapotranspiration in all structures evaluated is by more than 128 mm higher per a hydrological year. The difference in single structures is 59—185 mm (in structure of smaller altitude it is 155—169 mm, in structures of greater altitude — except the Harmanec syncline — it is 59 and 73 mm, in the Harmanec syncline even more than 185 mm). Also differences in values of balance-determined evapotranspiration in single hydrological years are higher than differences in value calculated by the above methods (Table 5—9).

In the evaluation of differences between values of evapotranspiration calculated from the balance equation and those determined by calculation method a significant factor neglected in calculation methods occurs, namely the high degree of afforestation of the structures evaluated (82—98 %, Tab. 4).

I think that the differences mentioned are mainly due to the influence of forest vegetation upon total evapotranspiration including interception, transpiration and evaporation. It is also proved by a comparison with the results of evapotranspiration evaluation in afforested areas in abroad and partly in our country, although the data do not concern fissure-karst rock environment. The data prove the increase in runoff controlled by the decrease in afforestation. Bosch and Hewlett (1982) published an extensive work and presented an opinion that chopping out and clearing in drainage area cause increasing runoff (decreasing evapotranspiration) whereas afforestation reduces runoff and increases evapotranspiration.

Dupraz—Didon—Lelong (1984) came to similar conclusions and published preliminary data on three experimental hydrogeological drainage areas in the region around Mont Lozére (France) under equal geological and climatic conditions and in average altitudes (1273, 1407, 1389 m. In Czechoslovakia Zelený (1969) expressed the same opinion after having found a relation between biomass decrease due to forest exploitation and increasing runoff. Zelený found out that approximately 36 % biomass decrease causes at leats 11.8 % increase in runoff in contrast to the period of exploitation calm.

The above mentioned data are in accordance with the results of the study of fissure-karst hydrogeologic structures in our country. Considering altitude of the structures in our country and of hydrogeological drainage areas abroad, we can see that the influence of afforestation upon evapotranspiration is still higher — according to foreign authors. But the hydrogeological drainage areas evaluated abroad are not situated in fissure-karst rock environment which may — under certain conditions — by better infiltation support increasing runoff in contrast to other hydrogeologic environments. It is also proved by much lower average evapotranspiration in the Muráň plateau hydrogeologic structure (527.9 mm) than in the Harmanec syncline (608.6 mm) although both structures have approximately equal altitude. But there are more favourable infiltration conditions (plain karst, rapid descent of precipitation) in the Muráň plateau.

The foreign literature does not offer enough comparative material for the evaluation of evapotranspiration differences in West Carpathian hydrostructures per single hydrological years.

Evapotranspiration increasing with the precipitation increase reffIects evidently more favourable conditions for evapotranspiration during hydrological years with above-average precipitation than in the years of deficient precipitation. The study of other factors like seasonal distribution of precipitation, its different intensity, variable conditions in single structures for infiltration through soil pack rock environment may result in data enabling precision of information about evapotranspiration per single hydrological years, particulary in fissure-karst structures.

Evapotranspiration is paid particular attention in this work because of great practical meaning of the knowledge of actual evaporation values in open hydrogeologic structures representing the most part of fissure-karst hydrogeologic structures of the West Carpathians. Then the data on prognostic natural groundwater resources in hydrogeologic structures may be precised by analogy. Hidden groundwater inflow from the structures into adjacent formations (Mesozoic, Tertiary and Quaternary sediments of lowlands and depressions, deep groundwater circulation from the structure a. o.) is mostly evaluated by balance methods. When calculation methods result in distorted (undervalued) data on evapotranspiration, then calculated values of hidden groundwater inflows from open structures to neighbouring formations are overvalued. This leads to unreal, optimistic prognoses in quantitative evaluation of groundwater in respect of its exploitation. It is a serious practical and theoretical problem because most structures in the West Carpathians including the fissure-karst structures show afforestation of a high degree. It is also economically important for extensive hydrogeological drilling for the purpose of catchment of presumably significant (actually small or no) groundwater inflow from mountain ranges to adjacent lowlands and depressions. There is a concrete example: Groundwater inflow from carbonate complexes of the Slovenský raj Mts. northwards into Mesozoic and Paleogene sediments of the Hornádska kotlina depression.

According to former opinions (Kullman 1964, 1968) there were favourable conditions for extensive groundwater inflow from the Slovenský raj Mts. into the Hornádska kotlina depression. New evaluations (Kullman 1985) considering substantially higher evapotranspiration proves that the inflow is much lower or none. The same concerns groundwater outflow from open fissure-karst hydrogeologic structures in the West Carpathians. So the hidden outflows from open structures must be quantitatively revaluated in respect of new data on evapotranspiration. Thus more exact information will be obtained about natural groundwater resources in hydrostructures and prospects of exploitation of groundwater inflow from structure to adjacent Paleogene — Quaternary sediments will be precised.

List of symbols

- Z — precipitation
- P_p — surface water inflow into hydrogeologic structure
- P_{pz} — groundwater inflow into hydrogeologic structure
- O_s — total runoff from hydrogeologic structure
- O_p — groundwater runoff by surface streams from hydrogeologic structure
- O_{pz} — groundwater runoff from hydrogeologic structure to surface (in springs, in outflows to surface streams, groundwater amount exploited from hydrogeologic structure)
- O_{pzh} — deep groundwater runoff from hydrogeologic structure
- E_b — evapotranspiration (determined from hydrologic balance equation)
- E_{BZ} — evapotranspiration (determined by Budyko-Zubenokova method)
- $\pm\Delta V_p$ — increase or decrease of water accumulation on structure surface (lakes, a. o.)
- $\pm\Delta R$ — groundwater reserves changes in rock environment of structure
- $\pm\Delta R_p$ — water reserves change in soil and humidity change
- O_z — effective precipitation
- H — altitude

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Relationship between hydrogeochemical characteristics of near--surface zone of rock massif and hydrodynamic conditions

Abstract. Quantitative relations between hydrochemical and hydrodynamic characteristics in the near-surface zone of a fractured rock massif were studied. The relations between groundwater chemical composition and hydrodynamic conditions were derived by theoretical analysis for a simple model of lateral flow toward a descending spring. In the relations studied the geomorphometrical parameter L/J is the best indirect index of hydrodynamic conditions. L — average filtration path length in the rock from infiltration to spring, J — average slope dip on the filtration path length. The L and J values may be determined from level line maps. The model is based on presumptive quasi-linear growth of concentrations of these variables in time.

Quantitative investigation of actual manifestations of theoretical regularities was done by means of correlation-and regression analysis of data on 342 descending springs in 23 regions of the Carpathians and the Bohemian Massif. In most cases there is a significant correlation between hydrochemical variables y (Ca-, HCO_3-concentrations, total dissolved solids) and the parameter L/J. The correlation may be expressed by linear regression equations like $y = a + bx$, where $x = L/J$.

The proposal of method of indirect estimation of the near-surface zone permeability in the area studied according to the determined value of the regression coefficient b is the main practical application. Then it is necessary to know the value of the water-rock interaction velocity.

The results of the investigation may also be applied to the monitoring of anthropogenic changes in geochemical processes (by the study of time changes in parameters of regression equations). The results may also serve as basis for the estimation of actual velocities of geochemical interactions between rock and water.

Introduction

The groundwater flow in rocks belongs among principal natural factors controlling the formation of chemical composition of groundwaters. The relationship between hydrogeochemical and hydrodynamical conditions has so far not been studied thoroughly from the quantitative view. This is why during the work on the II-4-8 national programme of basic research, coordinated by Faculty of Natural Sciences of the Comenius University in Bratislava in 1981—1985, the exploration concerning the relation between selected characteristics of chemical composition of groundwaters in fractured rocks and hydrodynamic conditions to check up the possible quantitative expression of these conditions proceeded in the partial task 05 "Methods of investigation of groundwaters in fractured rocks" at the Central Institute of Geology (Geological Survey) in

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Prague. The results were presented in unpublished reports (JETEL—RYBÁŘOVÁ 1983, 1985a, b). The purpose of this paper is to present detailed information about problems concerning the conditions in the near-surface zone, and some new data.

The groundwater circulation in fractured non-karstified rock masses with the exception of complexes with stratal aquifers, is mostly concentrated in a near-surface zone of increased permeability. Quantitative relations have mostly been studied in this zone since it is significant for the groundwater circulation and has quite accessible characteristics: permeability is determined by shallow hydrogeological and engineering-geological drilling, and hydrogeochemical data result from descending springs sampling.

Theoretical derivation of relation between groundwater chemical composition in near-surface zone and hydrodynamic conditions

Hydrogeological and hydrogeochemical conditions in near-surface zone

The near-surface zone is a zone of perisurficial desintegration of a rock massif with its mantle rock (JETEL 1983, JETEL—RYBÁŘOVÁ 1983a). In areas composed of hard non-karstified rocks without stratal aquifers the near-surface zone represents the main aquifer. In contrast to deeper parts of a rock massif it has a higher order permeability and its average permeability decreases regularly with increasing depth. The decreasing permeability may frequently be approximately described by exponential function (JETEL—RYBÁŘOVÁ 1975, 1983a; JETEL 1985a, KOVÁCS 1981). In the areas studied in the Carpathians and in the Bohemian Massif the near-surface zone mostly extends to depths about 20—40 m.

There is a transitional zone (to depth 80—100 m) beneath the near-surface zone. Its permeability is lower and still decreases regularly with the increasing depth. In depths below 80—100 m there are only scarce open fissures. They are distant from one another, distributed irregularly, so with respect to the reach of hydrodynamical tests in wells a quantitative expression of average permeability of the rock mass in such depths according to data of single wells is impossible (JETEL 1985c).

Detailed information on depth changes of permeability in near-surface and transitional zones may be obtained by injection tests performed in the course of engineering-geological exploration for dam profiles. Permeability characteristics from some parts of the Czechoslovak Carpathians have already been presented (JETEL—RYBÁŘOVÁ 1975, 1983a, b; JETEL 1985a). Data on depth changes in permeability from other areas were presented by KOVÁCS (1981).

The course of the near-surface zone is usually conformable with the ground surface. Precipitation water infiltrating into soil descends vertically through the aeration zone to the groundwater level, i. e. to the surface of the first groundwater accumulation in the rock mass (surface of the first groundwater body). Groundwater flow direction in the first groundwater body is mostly lateral, controlled by the ground surface dip. Groundwater of the first body issues partly in concentrated groundwater discharges — descending springs, the most part in dispersed runoff to surface streams and their alluvia. A small amount of water descends along isolated ways to deeper parts of the rock massif.

The first conspicuous changes in chemical composition appear on passing the soil stratum under a strong influence of biologic activity. After descending to the first groundwater body the chemical composition is controlled by reactions of water to rock. Concentration increase of some components may approximately be described as linear with time (cf. E. BUSENBERG—C. V. CLEMENCY 1976, T. PAČES 1983b, a. o.), and at constant flow velocity also as linear with the filtration path length. Linear approximation may be applied when the resulting solution is still considerably far from the equilibrium state.

Choice of variables for study

For the theoretical analysis of the relations studied it was necessary to select characteristics accountable for the study of a sufficient number of reliable quantitative data. The study of hydrochemical variables (JETEL—RYBÁŘOVÁ 1983b) showed that for the first stage of the research the total dissolved solids content M would be most suitable because it represents characteristics integrating the influence of hydrodynamic conditions in one resulting value. From components concentrations those controlled by hydrodynamic conditions have been selected. In the first phase of the research the concentrations of HCO_3^- and SO_4^{2-} were chosen. They dominate in anion composition of groundwaters studied and we already have stated pronounced relationship between these anions and some factors connected with hydrodynamic conditions (JETEL—RYBÁŘOVÁ 1978). Basing upon the results of the first research stage we abandoned the study of SO_4^{2-} concentrations but the components choice was extended by Ca^{2-}. In contrast to hydrochemical characteristics there is a limited possibility of direct determination of hydrodynamic characteristics in great numbers. We need indirect indices measurable directly in many points, whose values can indirectly indicate the effects of hydrodynamic characteristics.

Effective groundwater velocity u, i. e. the velocity of water transfer in a rock over the distance L_0 (L_0 — straight line distance in the course of filtration between two cross sections), is the principal hydrodynamic characteristics. It is determined by tracing tests from the time of the tracer displacement t_t over the distance L_0

$$u = L_0/t_t \qquad (1)$$

It equals to the ratio of volume discharge Q and active cross-section of pore channels A_a in the over-all flow cross-section A

$$u = Q/A_a \qquad (2)$$

The ratio of the cross-section of active pores which the water flows through (A_a) and the over-all rock cross-section (pores + grains) A is denoted as the effectiveness coefficient of the filtration cross-section

$$m_A = A_a/A \qquad (3)$$

It controls the relation between velocity u and darcian velocity(specific flux) v:

$$u = v/m_A \qquad (4)$$

Since the darcian velocity is according to Darcy's law expressed by the equation

$$v = k\,.\,J \qquad (5)$$

where k = hydraulic conductivity, J = piezometric gradient (groundwater level slope), the functional relation between velocity u and hydraulic conductivity k is expressed by the equation

$$u = k\,.\,J/m_A \qquad (6)$$

The equation (1) shows that velocity u controls the mean residence time when water is in contact with rock during displacement between two profiles in the distance, L_0:

$$t_r = L_0/u \qquad (7)$$

The time t_r is significant for the study of processes controlling chemical composition of groundwater during its flow through the near-surface zone. The equations (6) and (7) show that

$$t_r = \frac{m_A}{k} \cdot \frac{L_0}{J} \qquad (8)$$

In a rock environment with constant petrophysical properties the hydrodynamic conditions change first of all with the changing gradient J.

Changes of chemical composion during lateral flow in near-surface zone

Our theoretical analysis is based upon schematized process of formation of groundwater chemical composition by the "water-rock" interactions when the mass balance equation is valid (PAČES 1976)

$$\frac{\partial M_i}{\partial t} = \frac{1}{m_e}\frac{dq}{dt} + D_i\frac{\partial^2 M_i}{\partial x^2} - u\frac{\partial M_i}{\partial x} \qquad (9)$$

where M_i = molar concentration of i-component in water, t = duration of reaction, m_e = rock porosity effective in respect of water-rock interaction ("chemically effective porosity"), q = number of moles of i-component exchanged between rock unit volume and water, D_i = coefficient of i-component diffusion in water, x = spatial coordinate in direction of filtration, u = effective flow velocity in the direction of axis x. The following equations are valid for a stationary system with a negligible diffusion effect

$$\partial M_i/\partial t = 0 \tag{10}$$

and

$$D_i\, \partial^2 M_i/\partial x^2 = 0 \tag{11}$$

so that equation (9) is simplified to

$$\frac{1}{m_e}\frac{dq}{dt} - u\frac{dM_i}{d_x} = 0 \tag{12}$$

In the first approximation it may be supposed that the exchange velocity between rock and water d_q/dt and porosity m_e are constant over the entire filtration path considered, i. e. that

$$dq/dt = \text{const.} \tag{13}$$

$$m_e \quad = \text{const.} \tag{14}$$

Thus the constant

$$C_1 = (l/m_e) \, . \, (dq/dt) = \text{const.} \tag{15}$$

enters the relations considered.

From the equation (12) the following relation follows for the concentration increment ΔM_i acquired over the length x = L:

$$C_1 L - u\,\Delta M_i = 0 \tag{16}$$

$$\text{i.e.} \quad \Delta M_i = C_1 L/u \tag{17}$$

The near-surface zone rock environment with lateral water flow from infiltration to a descending spring may be schematized as hydraulically homogeneous (k = const., m_A = const.) for our purposes. Thus another constant enters the relations studied

$$C_2 = k/m_A = \text{const.} \tag{18}$$

Then in the sense of the equation (6) the effective velocity u only changes with the gradient J

$$u = C_2 \, . \, J \tag{19}$$

The piezometric (hydraulic) gradient J is particularly important for the study of relations between hydrogeochemical and hydrodynamical conditions, because it may be quite easily determined without any special operations, the first groundwater body level being more-or-less conformable with the ground surface. We presume an approximate conformity between the dip of the first groundwater body level and the average dip of the ground surface, which may be read from level lines of a map. So the average dip of the ground surface in the area of the formation and movement of the first groundwater body is regarded as the indirect characteristics of its hydrodynamic conditions.

The expression of the effective velocity u in the equation (17) by (19) results in a simple relation

$$\Delta M_i = \frac{C_1}{C_2} \frac{L}{J} \tag{20}$$

When the simplifying conditions of constancy (13), (14), (18) are accepted then in the sense of the equation (20) the changing concentration of the component i in the first groundwater body at lateral filtration during rocks is directly proportional to the filtration path length L and inversely proportional to the first groundwater body level dip J. The relation is invalid when water comes near to chemical equilibrium.

As regards descending springs, the value L in the equation (20) represents the average distance between infiltration to the first groundwater body and the spring. J represents here the average ground dip over the length L above the spring. According to the equation (20) the change of concentration M_i over the length L is directly proportional to the L/J ratio denoted as a "reduced filtration path" (J. JETEL—L. RYBÁŘOVÁ 1983b). The geomorphometric characteristics of the descending spring L/J may be read from a level line map.

The actual meaning of L/J may be characterized as the distance in the near-surface zone over which water advances in a hillside with a dip J = 1 during the respective water residence time in the near-surface zone t_r, because in accordance with (8)

$$L/J = t_r \, . \, k/m_A \tag{21}$$

For example: In a near-surface zone with the average hydraulic conductivity $k = 1 \times 10^{-5} . s^{-1}$ and the average value $m_A = 0{,}105$ the reduced filtration length L/J = 3000 m will correspond to the water transport time $t_r = 1$ year. The L/J value will equal to the actual filtration length L if the average slope dip will be 45° (J = 1). On moderate slopes (with a lesser J) the actual average filtration length L will be adequately smaller for the same time t_r. During practical study of single spring the value L was replaced by the horizontal projection L_h of the actual length L_r to enable direct measurements of L values in a map. According to

$$L_r = \sqrt{L_h^2 + H^2} = \sqrt{L_h^2 (1 + J^2)} \tag{22}$$

the actual length L_r is greater (H = altitude difference between infiltration and spring), but in the areas studied the differences may be neglected because at the maximum average dips (about J = 0,55) the ratio L_r/L_h is only 1.14 (the error in L_r determination is less than 12 %).

The velocity of the transition of the i component from rock to water dq/dt will be denoted as w_i:

$$w_i = dq_i/dt \tag{23}$$

In the sense of equation (13) we use a simplifying presumption about constant exchange velocity. PAČES (1973) reasoned kinetically the validity of this presumption for feldspars but it is not generally valid for carbonates (PLUMMER et al. 1978).

After writing out the constants C_1 and C_2 according to (15) and (18) the proportionality coefficient between increment ΔM_1 and parameter L/J may be expressed as

$$\frac{C_1}{C_2} = \frac{w_i/m_e}{k/m_A} = \frac{w_i}{k} \cdot \frac{m_A}{m_e} \tag{24}$$

After presenting all partial coefficients the equation (20) will acquire the form of

$$\Delta M_i = \frac{w_i}{k} \cdot \frac{m_A}{m_e} \cdot \frac{L}{J} \tag{25}$$

Model of formation of descending spring water chemical composition

The above ideas imply a schematization of the formation of descending spring water chemical composition in a certain simple model which may be described as follows:

1. a relatively short vertical descent of infiltrated water through soil and unsaturated zone to the first groundwater body (saturated part of near-surface zone),
2. a descending-lateral groundwater movement in the saturated part of the near-surface zone over the slope from infiltration to the spring,
3. an approximate accordance between the average dip of the first groundwater body level during the descending-lateral movement with the average dip of ground surface (slope),
4. a quasi-linear growth of M_i concentration of the considered i component with the lateral filtration length L,
5. a partial outlet of groundwater from the near-surface zone to the surface in the form of a descending spring.

The scheme of the spatial structure of the model is given in Fig. 1. The resulting concentration M_i of the i component behaving in accordance with the model will then in the descending spring water be determined by the relation

$$M_i = M_{io} + \Delta M_i \tag{26}$$

where M_{io} = initial concentration entering the process of the quasi-linear growth — i. e. concentration in water after the vertical descent through the soil and unsaturated zone to the lateral flow, ΔM_i = increase in concentration during lateral flow from infiltration to the spring, determined by (20) and (25).

Statistical relation between chemical composition of descending spring water and indirect hydrodynamic characteristics

The study of statistical relations between hydrochemical and hydrodynamical characteristics of the near-surface zone concerned at first the relations among several selected characteristics, and possible optimal expression of the relations in the most suitable type of regression equation. It was evident that the relations would mostly be discernible in concentrations of components whose transition from rocks to water may be approximately described by regular growth of concentration during the lateral flow through the near-surface zone. Concentrations of the components reflect the duration of contact between water and rock, expressed by (8). Primarily most suitable seemed to be concentrations of HCO_3^- and total dissolved solids M, in the second phase also Ca^{2+} concentrations. In the first phase also relative information entropy H_r expressing the internal vagueness of the chemical type of water was studied as integral hydrochemical characteristics (JETEL 1975, 1987b).

In the first phase among indirect hydrodynamical characteristics besides the values of the L/J parameter also the values of gradient J (estimated as the average slope dip above the spring) and values of the spring altitudes h were studied.

In the first phase correlation closeness was examined for regression equations of the following types:

— linear regression equation of the type

$$y = a_1 + b_1 x \qquad (27)$$

$$(y = M, HCO_3; \quad x = J, L/J, h),$$

— regression equation of the type

$$\log y = a_2 + b_2 x \qquad (28)$$

$(y = M, HCO_3; x = J)$, also expressible as exponential regression equation

$$y = a_3 e^{b_3 x} = a_3 \exp(b_3 x) \qquad (29)$$

— regression equation

$$\log y = a_4 + b_4 \log x \qquad (30)$$

$(y = M; x = J)$, from which the hyperbolic regression equation

$$y = a_5 / x^{b_5} \qquad (31)$$

has been derived.

The data from various Czechoslovak regions underwent the correlation- and regression analyses in the first and second phases. The purposes of the analyses of single data populations were:

a) to prove the existence of a statistically significant correlation between the variables studied,

b) to evaluate the closeness of the correlation,

c) quantitative expression of the statistic relation by a regression equation in the selected form.

Results of the Ist phase (JETEL—RYBÁŘOVÁ 1983b) show that the linear regressing equation of the type (27) is most suitable for expressing the statistical relation of concentrations of selected components or total dissolved solids to morphometric characteristics (L/J). So in the second phase the relations studied were only expressed by equations of the type

$$y_i = a_i + b_i x, \tag{32}$$

where x = independent variable (morphometric characteristic L/J); y = dependent variable (hydrochemical characteristics: M, HCO_3, Ca), a_i = locating regression constant, b_i = regression coefficient, i = index specifying the component studied. In the 2nd phase the analysis resulted in calculation of sample coefficient of linear correlation r for each population, evaluation of statistical significance of linear correlation and calculation of parameters (a_i, b_i) of equation (32). The criterion $t = \sqrt{n-2} \, . \, |r|/\sqrt{1-r^2}$ (G. KORN—T. KORN 1961, AIVAZIAN 1970, BAKYTOVÁ et al. 1979 a. o.) judged according to Student's distribution probability tables (BOLSHEV—SMIRNOV 1983), was applied on testing the hypothesis about the accordance of calculated sample coefficient of linear correlation r with the zero correlation coefficient of the general population. Significance of the ascertainment of linear correlation was characterized by significance level p: the probability P of actual existence of linear correlation in a general population whose random sample is represented by treated data is given by the relation $P = 1 - p$ or $P = (1 - p) \, . \, 100$ %. The value of Spearman coefficient of consecutive correlation (G. KORN—T. KORN 1961) was the preliminary criterion of statistical significance. If it showed insignificance of correlation, further regression and correlation analyses were omitted.

Results of correlation- and regression analyses from particular regions

Particular populations of data for the regression- and correlation analyses were formed in regions with reliable data on chemical composition of descending springs water corresponding to the model accepted, and with reliably marked situations of springs in detailed level-line maps. In respect of the first condition, the regions with a dissected, frequently mountain relief prevailed.

A model population of data on springs in Vihorlat and Popričný Mts.

At first it was necessary to prove on a selected model population of concrete data, that theoretically derived relations were exhibited in relations of actually measured values, and that the relations may be studied by statistical analyses and characterized quantitatively. A population of 27 data on descending springs in neovolcanic mountain ranges Vihorlat and Popričný (E. Slovakia; SZABOVÁ 1976) was used for that purpose. It is a region composed of a stratovolcanic massif of Miocene effusive rock complex (mostly andesites) and their volcanoclastics. The data resulted from mapping (SZABOVÁ 1976) during regional hydrogeological exploration performed by IGHP Košice (BAJO et al. 1976).

The environment of groundwater flow is from the most part formed by pyroxenic andesites mostly composed of plagioclases and pyroxenes. Andesite pyroclastics are less frequent. Waters of the springs studied are mostly silicatogenic — according to GAZDA (1974), with a variable portion of the carbonatogenic component. In Alekin's classification (ALEKIN 1970) they are mostly waters of the $Ca\text{-}HCO_3$ group with T.D.S. 0.06—0.30 $g.l^{-1}$. Springs from andesites mostly represent the C_{I}^{Ca} type, less frequently C_{II}^{Ca} and C_{IIIa}^{Ca}. Low-mineralized waters (to 0.07 $g.l^{-1}$) issuing near mountain tops and ridges occasionally also represent the types S_{IIIa}^{Ca}, N_{IIIb}^{Ca} and C_{IIIb}^{Ca}. In Gazda's classification (GAZDA 1971) they are mostly basic type waters $Ca\text{-}HCO_3$ (A_2 averagely 69 eq %, $r(Ca/Mg) = 2.0—4.8$).

The original population comprised 23 springs issuing from andesites and volcanoclastics and 4 springs from Paleogene sandstones on the mountain range periphery. For this population the analysis of possible relations in equations of different forms (27)—(31) at different combinations of the variables was done.

Relations between chemical composition of water and slope dip J

In the first phase the relation of total dissolved solids M and the HCO_3^- concentration to the slope dip was examined at first. The value J was not determined as the average dip between the spring and the infiltration area (Fig. 1) but as the average dip of a characteristic part of the slope immediately above the spring. It was difficult to calculate the dip J for springs issuing in the ridge- and top parts recharged almost directly with precipitation water. The actual surface dip, considerably reduced at ridges, is almost insignificant for formation of chemical composition of waters. In such cases the ridge springs were allotted the value $J = 0.55$ surpassing the maximum actual measured dip values about $J = 0.50$. In Fig. 2—4 the points are separated from the field of actual measured dips and marked with t.

Since the plotting of values M vs. J showed a distinctly curvilinear course of the presumable regression line (cf. Fig. 2), an equation of the type (28) was used to express the relation $M = f(J)$. For 29 data the equation has the form

$$\log M = 2.406 - 1.132\, J \qquad (34)$$

(M = total dissolved solids in $mg.l^{-1}$) with the linear correlation coefficient $r = -0.86$ (Fig. 3). The dashed line corresponds to a modified line for 25 points

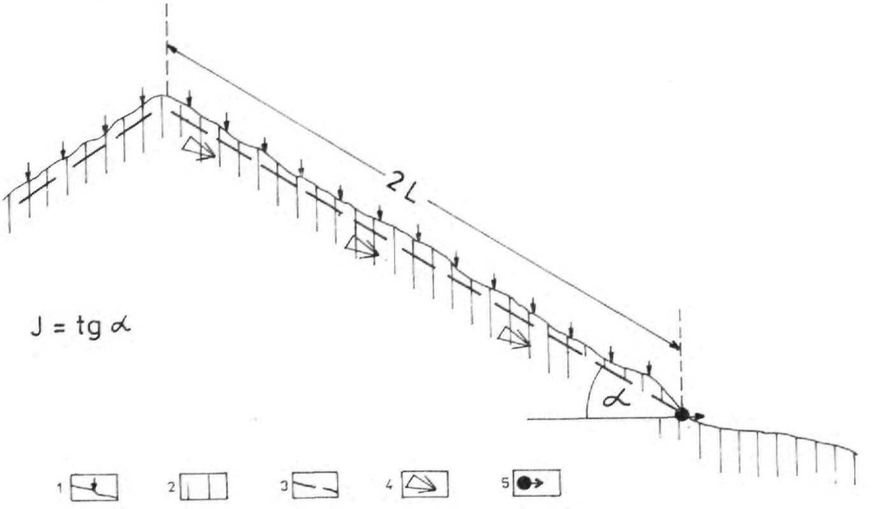

Fig. 1 Scheme of model of descending spring feeding
1 — infiltration, 2 — near-surface zone, 3 — first groundwater body level, 4 — lateral — descending flow, 5 — spring

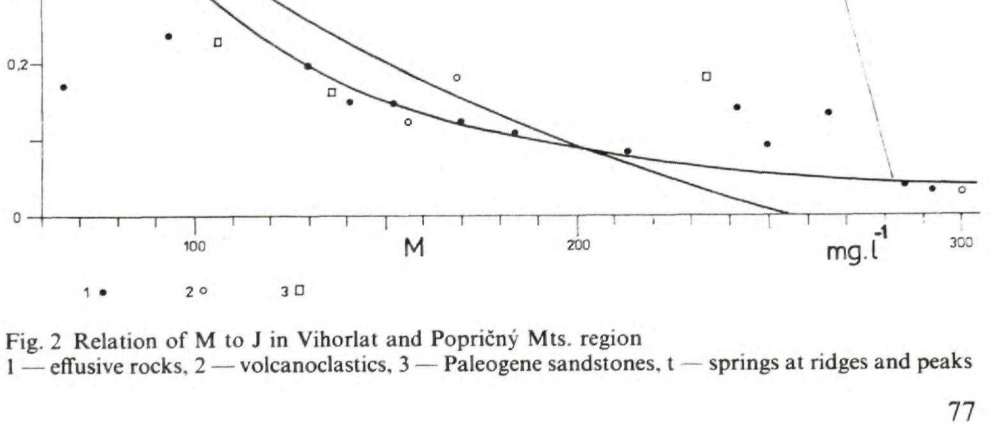

Fig. 2 Relation of M to J in Vihorlat and Popričný Mts. region
1 — effusive rocks, 2 — volcanoclastics, 3 — Paleogene sandstones, t — springs at ridges and peaks

after eliminating the ridge springs with allotted values J = 0.55. Because of a negligible difference from the line (34) the points with J = 0.55 were not eliminated anymore. An exponential equation of the type (29) in the form

$$M = 255\, e^{-2.6065\, J} \tag{35}$$

corresponds to the linear relation (34).

The distribution of points on the curves x = J, y = M (Fig. 2) indicates a probable deviation of the actual relation from the exponential relation (35) in ranges of minimum and maximum values, and possible approximation of the relation examined by the (31) type hyperbole. The hyperbolic expression is logical because there evidently exist the minimum non-zero values M also at the "infinitely great" J (precipitation water after transit through the soil zone) and vice versa: even at the minimum (zero) dip the value M would not exceed certain maximum corresponding to equilibrium. So the relation of the type (30) was examined for quantitative expression of the hyperbolic relation. For the given sample set it has the form

$$\log M = 1.703 - 0.579 \log J \tag{36}$$

(M in $mg \, . \, l^{-1}$) with the linear correlation coefficient $r = -0.88$. The equation of the type (31) hyperbole

$$M = 50.47 / J^{0.579} \tag{37}$$

(Fig. 2) corresponds to the equation (36). Fig. 2 shows a better accordance between the hyperbolic relation and measured data than the exponential relation at dips lesser than J = 0.2, i. e. for M = 100—300 $mg \, . \, l^{-1}$ (particularly after

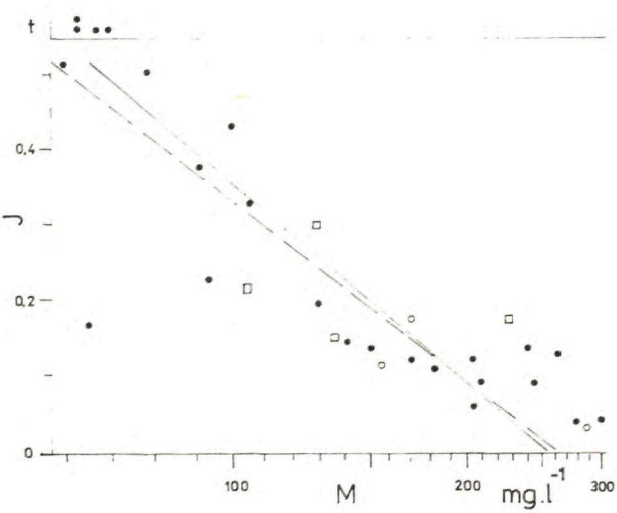

Fig. 3 Relation of log M to J in Vihorlat and Popričný Mts. region. For explanations see Fig. 2.

the exclusion of springs out of effusive rocks). Five points from effusive rocks are directly on the hyperbole (120—200 mg . l^{-1}). At higher dips ($J > 0.2$) the points are more dispersed around the hyperbole and the exponential curve.

The correlation coefficient values of equations (34) and (36) with the corresponding determination coefficient $r^2 = 0.76$—0.77 indicate that total dissolved solids content of springs in the region Vihorlat—Popričný is approximately in 3/4 controlled by the dip of slopes above springs whereas other factors (petrographic character of rocks, variable permeability and porosity of the near-surface a. o.) only control 1/4 of M and its variability.

The relation of the HCO_3^- concentration to the dip J has been examined in analogy with the relation $\log M = f(J)$ and is expressed in the equation (Fig. 5)

$$\log HCO_3^- = 2.149 - 2.088\ J \qquad (38)$$

(HCO_3^- in mg . l^{-1}) with coefficient $r = -0.74$. The equation may be rewritten in the exponential form (28)

$$HCO_3 = 141\ e^{-4.808\ J} \qquad (39)$$

Fig. 4 also gives the SO_4^{2-} concentration. The diagram shows that the mutual relation of SO_4^{2-} and HCO_3^- concentration is controlled by the slope dip like in the Moravskosliezske Beskydy Mts. (Jetel—Rybářová 1978): HCO_3^- concentrations increase with the decreasing dip while SO_4^{2-} concentrations do not show any relation to the dip J. The SO_4^{2-}/HCO_3^- concentrations ratio is highest with springs issuing near ridges and below steep slopes. The ratio decreases with the decreasing dip of slopes. Statistical relation between SO_4^{2-} concentrations and the dip J cannot be proved (Fig. 4). It suggests that the sulphates in waters examined originate most likely from precipitation or on passing the soil- and unsaturated zone.

The idea of processes forming groundwater chemical composition in the region studied indicates that with the increasing M and decreasing J statistically related to M according to equations (34)—(37), the composition of waters will advance towards the pure Ca-HCO_3 type or towards the conspicuous basic type A_2 in the sense of Gazda's classification. To prove this assumption for particular springs we have expressed the vagueness of chemical composition by internal relative information entropy H_r (Jetel 1975, 1987b). The more distinct the chemical composition, the lower the H_r value. If the water consists of only one of N possible components — for example $A_2 = 100$ %, then $H_r = 0$. If the portions of all N possible components are equal (for $N = 6$ they equal 0.167), then $H_r = 1$. The relation $H_r = f(J)$ underwent the correlation- and regression analyses. Statistically significant linear relation of H_r to J for 22 springs issuing from andesites and volcanoclastics is expressed by the regression equation

$$H_r = 0.376 + 0.876\ J \qquad (40)$$

with the coefficient $r = 0.783$ (determination coefficient $r^2 = 0.61$).

The analysis of relations between hydrochemical characteristics and dip J

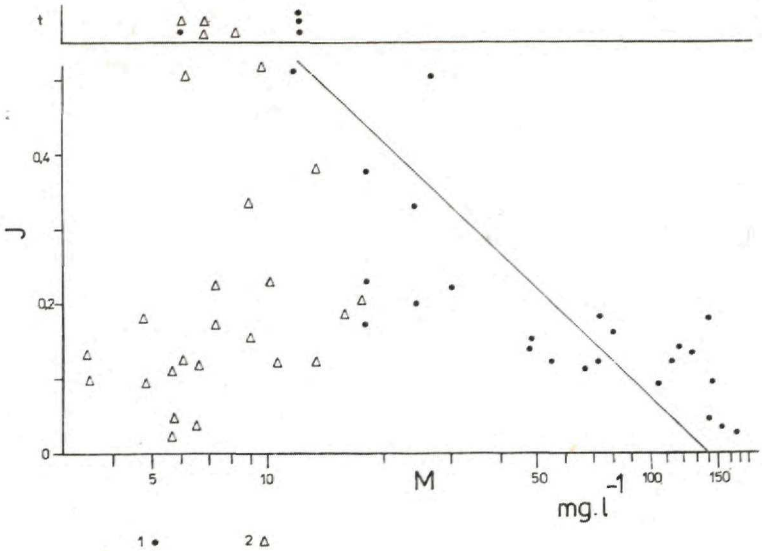

Fig. 4 Relation of log HCO_3 to J in Vihorlat and Popričný Mts.
1 — concentrations HCO_3^-, 2 — concentrations SO_4^{2-}, t — springs near ridges and peaks

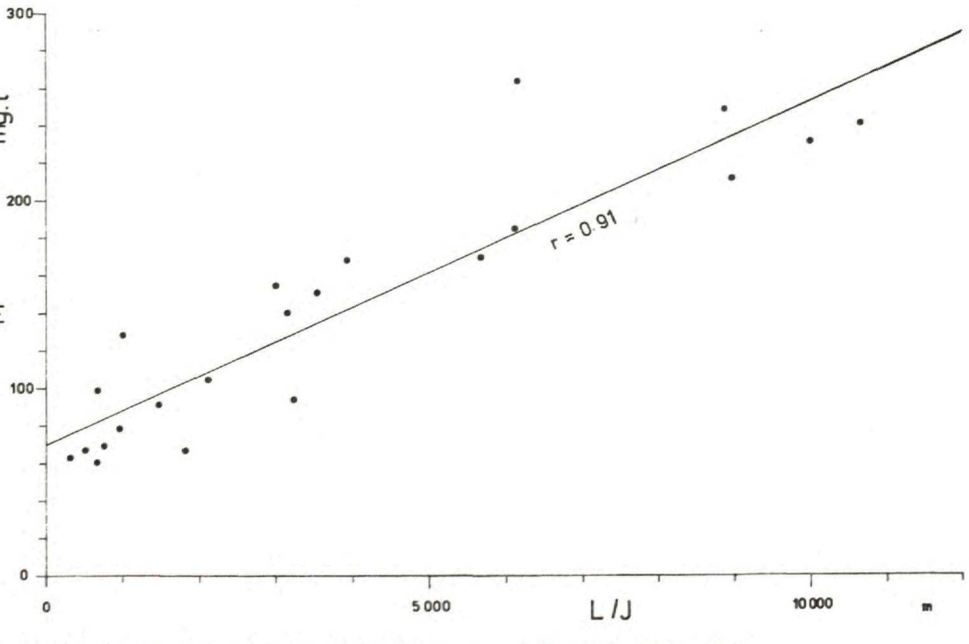

Fig. 5 Relation of M to parameter L/J in Vihorlat and Popričný Mts. region

shows that correlations with J are more-or-less unambiguous and decisive for the formation of chemical composition of the first groundwater body only in areas with concave slopes where the dip decreases from the infiltration area to the spring, or there where the slope dip does not change from infiltration to spring. In areas with convex slopes (with a moderate dip in the infiltration area and with a steep slope above the spring) the water level dip above the spring is almost insignificant: water with mineralization representative of chemical composition formed in a gently dipped distant area flows to the spring over a steep slope. During further research the value of the geomorphometrical parameter L/J was viewed as more representative and reliable hydrodynamical characteristics.

Relations between chemical composition of water and parameter L/J

Statistically significant relations of M and HCO_3^- to the reduced filtration path length L/J were already proved by data from the Vihorlat and Popričný Mts. evaluated in the lst phase of the research (JETEL—RYBÁŘOVÁ 1983b). Since it was the first region studied, the determination of the average filtration path values L for individual springs was not uniform. The L values were not determined thoroughly according to the model presented in Fig. 1 but they frequently were close with the distance of the spring from the groundwater divide. So the values L and L/J used in the first evaluation of the model population were overestimated in comparison with later precised lengths L (for the simplest case of a slope with more-or-less constant dip between the spring and the divide — Fig. 1 — as a half-distance from the spring to the divide). Quantitative expressions of relations to the values L/J calculated in the first research phase for the model population thus do not agree with the expressions derived later for other regions.

Later on the L/J values concerning springs in the Vihorlat and Popričný Mts. were revised so as to correspond with values concerning the later evaluated regions and to be comparable with the respective regression coefficient values. The range of the original model population was reduced to springs issuing from the area of effusive and volcanoclastic rocks (springs from Paleogene sandstones were excluded). We have also omitted springs with extremely high values L/J = 29, 38 and 48 km from mountain range peripheries, because they were not characteristic of the respective region. For springs on ridges and mountain peaks the actual values J were used (distortion due to small dip J on ridges and on flat peaks is compensated by small length L).

Statistical relation of spring water total dissolved solids M to geomorphometric parameter L/J (Fig. 5) for the reduced model population of 22 data on springs issuing from andesites and volcanoclastics is expressed by the linear regression equation of the type (27) or (32)

$$M = 70.9 + 0.0182\ L/J \tag{41}$$

(M in mg.l^{-1}, L in metres) with the linear correlation coefficient $r = 0.909$ (determination coefficient $r^2 = 0.826$).

The relation of HCO_3^- concentration to the reduced length of filtration L/J is for the reduced population of 22 data (Fig. 6) expressed by the equation

$$HCO_3 = 7.4 + 0.0122\ L/J \tag{42}$$

(HCO_3 in mg.l^{-1}) with the coefficient $r = 0.927$ ($r^2 = 0.859$). For the same population also the relation of Ca^{2+} concentration to L/J (Fig. 7) was examined. It is expressed by the equation

$$Ca = 6.5 + 0.00182\ L/J \tag{43}$$

(Ca^{2+} in mg.l^{-1}) with $r = 0.905$ ($r^2 = 0.820$).

Determination coefficients of the relations (41)—(46) indicate that in descending springs issuing from effusive and volcanoclastic rocks in the Vihorlat and Popričný Mts. the dissolved solids M and HCO_3^- and Ca^{2+} concentrations in water are controlled in 82—86 % by the reduced filtration length L/J, and differences in the characteristics are only in 14—18 % due to other factors. As for the correlation closeness it is to be noticed that it is extremely high in spite of inhomogeneity of the population due to different positions of hydrochemical characteristics in the course of periodical (seasonal, regime) changes of chemical composition. Most samples were taken in April 1973, less samples were taken in May 1975 and in spring, summer and autumn of the years 1971 and 1972. Perhaps at a simultaneous sampling the correlation closeness could be even higher. For the sample population of 22 data, the correlation determined for the relation (41)—(43) is statistically significant on the significance level $p < 0.001$ (i.e. with probability higher than $P = 0.999$ (99.9 %).

The values of constants a_i in the equations (41)—(43) show that water with the average total dissolved solids $M = 71$ mg.l^{-1} and with average Ca^{2+} and HCO_3^- concentrations about 7 mg.l^{-1} enters the process of quasilinear growth of mineralization in the area of the Vihorlat and Popričný Mts. The input concentrations reflect the precipitation water mineralization and its changes during vertical descent through soil- and unsaturated zone. During lateral descent through the near-surface zone to springs (Fig. 1), according to regression coefficients b_i values the HCO_3^- concentration increases by 0.012 mg.l^{-1}, Ca^{2+} concentration by 0.0018 mg.l^{-1} and M by 0.018 mg.l^{-1} per 1 m of reduced filtration length L/J (i.e. per 1 m of actual filtration length on slopes dipping at 45° – J = 1 –). Similar quantitative interpretation is possible for regression equations derived for statistically significant relations between hydrochemical characteristics and L/J in other regions studied.

Statistically significant relation of the internal relative information entropy H_r to the slope dip J also reflects in the relation of H_r to the L/J values. This is indirect proportionality. It is expressed for the reduced population of 22 data on the Vihorlat and Popričný Mts. by the regression equation

$$H_r = 0.793 - 4.823 \times 10^{-5}\ L/J \tag{44}$$

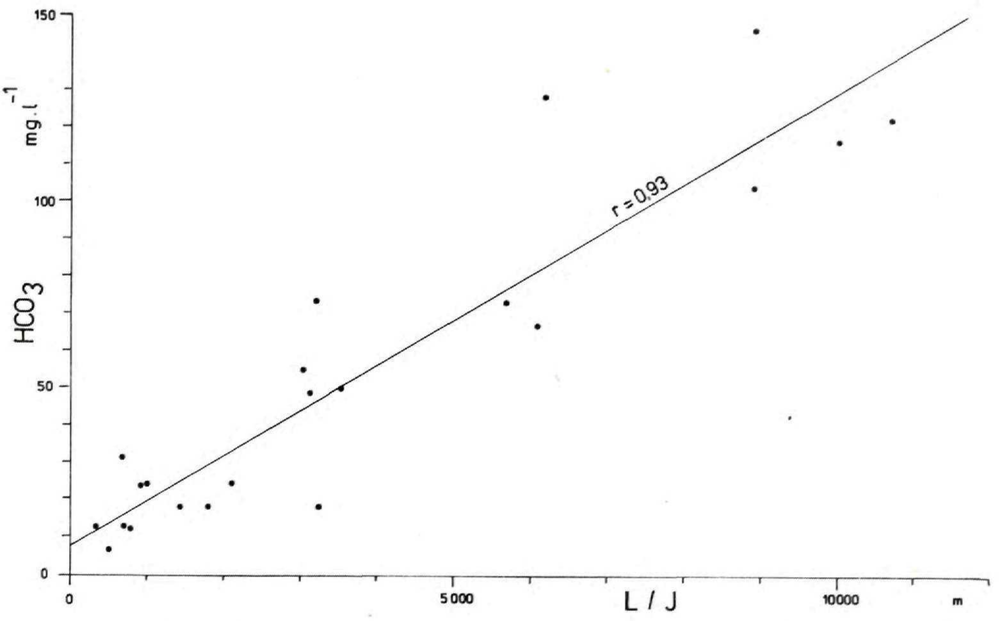

Fig. 6 Relation of concentration HCO_3^- to parameter L/J in Vihorlat and Popričný Mts. region.

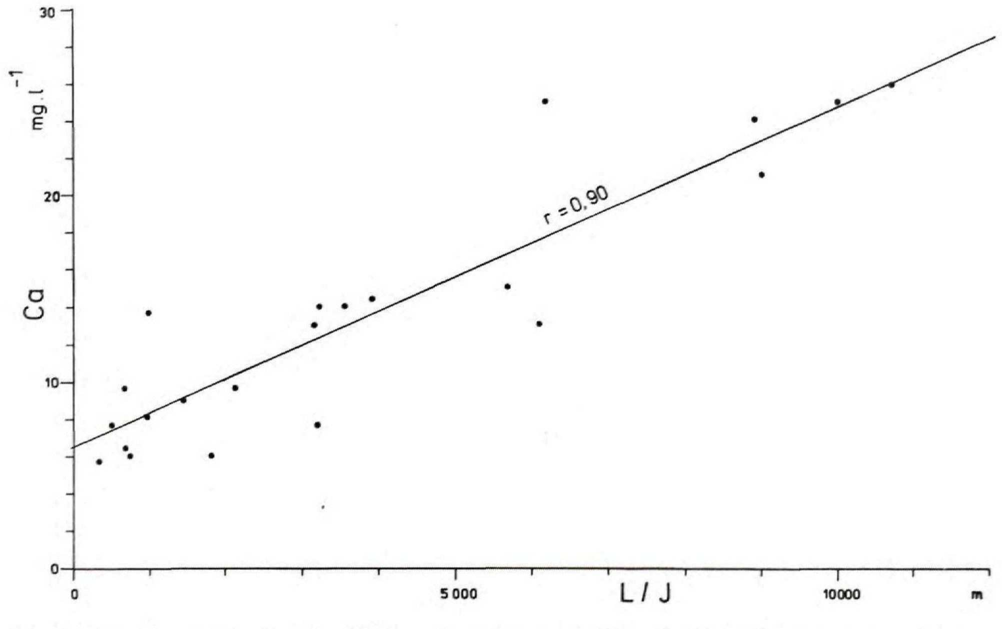

Fig. 7 Relation of concentration Ca^{2+} to parameter L/J in Vihorlat and Popričný Mts. region.

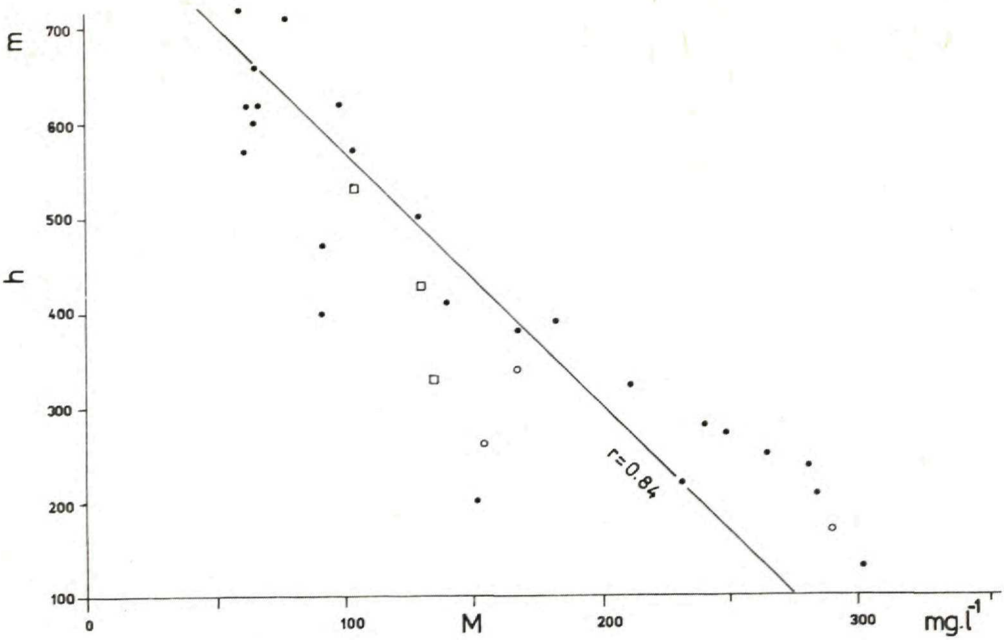

Fig. 8 Relation of M to spring altitude h in Vihorlat and Popričný Mts. region (h — expressed in m). For explanations see Fig. 2.

($r = 0.835$, $r^2 = 0.70$). The relation (44) shows that waters of indistinct type with high values of H_r (0.71—0.99) and extremely reduced filtration lengths (L/J) from the ridge- and mountainpeak areas, after a longer lateral flow on slopes and with increasing M get closer to the distinct Ca-(Mg)-HCO_3 type with the A_2 component dominant (81—85 %) and with H_r values decreasing to minima about $H_r = 0.34$.

Evaluation of other regions

The detailed analysis of the model population data was followed by the correlation and regression analyses of populations of data on springs in other regions of the West Carpathians and of the Bohemian Massif with a reduced number of the relations studied to the dip J in the 1st phase of the research (JETEL—RYBÁŘOVÁ 1983b). In the 2nd phase (JETEL—RYBÁŘOVÁ 1985a, b) only the relations to L/J values were studied. The results of the correlation and regression analysis of particular populations are given in Tables 1—5 and in Figures 9—12.

The results of the study of hydrogeochemical characteristics in relation to the reduced filtration length L/J presented in Tables 3—5 and in Fig. 10—12 concern the following 23 populations:

Table 1 Results of correlation and regression analysis of relation $\log M = f(J)$

Region	n	r	a	M(a)	b	$\bar{x}$	$\bar{y}$	M($\bar{y}$)
Vihorlat-Popričný Mts. — neovolcanics (+ Paleogene)	29	−0.86	2.406	255	−1.132	0.24	2.132	136
Moravsko-slezské Beskydy Mts. —Godula Formation (population 2)	71	−0.16	2.142	139	−0.215	0.38	2.068	117
Moravsko-slezské Beskydy Mts. — Istebna Member (population 3)	30	−0.42	2.086	122	−0.422	0.29	1.930	85
Kysucké Beskydy Mts. — Kyčera Member (population 9)	15	−0.50	2.625	422	−0.977	0.45	2.187	154
Biele Karpaty Mts. (population 10)	10	(R = −0.16)						
Lužické hory Mts.- Cretaceous sandstones (population 11)	8	(R = 0.31)						
Lower-Silesian Basin — Carboniferous (population 12)	9	(R = −0.03)						
Krkonoše Mts. — E part (population 22)	15	−0.27						

Regression equation: $y = a + bx$ Variables: $x = J$, $y = \log M$
M = T. D. S. ($mg.l^{-1}$) J = slope dip above spring
n = number of data r = linear correlation coefficient
R = Spearman coefficient of correlation
a = locating regression constant
b = regression coefficient
$\bar{x}$, $\bar{y}$ = arithmetic means of variables
M(a), M($\bar{y}$) = mineralization corresponding to values a and $\bar{y}$.

Neovolcanics of the Carpathian system:

1. andesites and volcanoclastics of the Vihorlat and Popričný Mts. (number of data n = 22),

Carpathian Flysch-Silesian Unit:

2. the Godula Member of the Moravsko-Slezské Beskydy Mts. (n = 71),
3. the Istebna Member of the Moravsko-Slezské Beskydy Mts. (n = 30),

Carpathian Flysch — Rača Unit of Magura Group:

4. the Hostýn Member of the Hostýnské vrchy Mts. (n = 10),
5. the Rusava Member of the Hostýnské vrchy Mts. (n = 11),
6. the Soláň Member of the Hostýnské vrchy Mts. (biotite facies) (n = 26),
7. the Luhačovice Member of the Komonecká hornatina upland (n = 9),
8. the Vsetín Member of the Hostýnské vrchy Mts. and NE part of the Gottwaldovská vrchovina upland (n = 12),
9. the Kýčera Member of the Kysucké Beskydy Mts. (n = 15),

Carpathian Flysch — Bystrica and Biele Karpaty units of Magura Group:

Table 2 Results of correlation and regression analysis of relation M = f(h)

Region	n	r	a	b	$\bar{x}$	$\bar{y}$
Vihorlat-Popriečny Mts. — neovolcanics (+ Paleogene)	30	−0.84	312	−0.374	424	154
Kysucké Beskydy Mts. — Kyčera Member (population 9)	15	−0.35	215	−0.0657	751	166
Krkonoše — E part (population 22)	15	−0.81	293	−0.198	1007	82
Nízke Tatry Mts. — NE slopes (dolomites)	36	−0.74	789	−0.517	837	355

Regression equation: $y = a + bx$ Variables: $x = h$, $y = M$
h = spring altitude (m above sea level)
M = T. D. S. ($mg.l^{-1}$)
(n, r, a, b, $\bar{x}$, $\bar{y}$ — like in Tab. 1)

Table 3 Results of correlation and regression analysis of relation M = f(L/J)

Population	n	a	b	r	p
1	22	71	0.0182	0.91	<0.001
2	71	76	0.0129	0.46	<0.001
3	30	64	0.0117	0.37	0.05
4	10	232	0.141	0.67	0.03
5	11	(194)	(0.0873)	0.26	0.44
6	26	236	0.0667	0.46	0.02
7	9	104	0.00447	0.51	0.16
8	12	213	0.159	0.44	0.15
9	15	117	0.0631	0.57	0.03
10	10			0.20*	
11	8	77	0.00141	0.58	0.14
12	8			−0.23*	
13	8			−0.05*	
14	5			0	
15	9	(223)	(0.00671)	0.29	0.45
16	21	67	0.00265	0.62	0.003
17	17	44	0.0127	0.81	<0.001
18	6	(137)	(0.00259)	0.27	0.62
19	10	70	0.0335	0.74	0.015
20	11			−0.23*	
21	8	−149	0.113	0.90	<0.001
22	15	31	0.0312	0.68	0.002
23	23	20	0.0408	0.69	<0.001

Regression equation: $y = a + bx$ Variables $y = M$ $x = L/J$
M = T. D. S. ($mg.l^{-1} = g.m^{-3}$)
L/J = reduced filtration length (m)
n = number of data
a = locating regression constant
b = regression coefficient
r = linear correlation coefficient (values denoted with * are values of Spearman coefficient of rank correlation)
p = significance level of correlation found out

Table 4 Results of correlation and regression analysis of relation $HCO_3 = f(L/J)$

Population	n	a	b	r	p
1	22	7.4	0.0122	0.93	<0.001
2	71	25	0.00531	0.30	0.02
3	30			0.05	
4	10	84	0.109	0.74	0.01
5	11	28	0.117	0.52	0.10
6	26	99	0.0504	0.49	0.02
7	9	48	0.0224	0.45	0.22
8	12	108	0.126	0.54	0.07
9	15	66	0.0370	0.48	0.07
10	10			0.40*	
11	8	15	0.00104	0.69	0.06
12	8	8	0.00621	0.86	0.01
13	8			−0.24*	
14	5			0	
15	9			0.19	0.74
16	21	(18)	(0.000285)	0.19	0.41
17	17	(17)	(0.00118)	0.26	0.32
18	6			0.33*	
19	10	28	0.0244	0.70	0.02
20	11			−0.26*	
21	8	−148	0.0802	0.93	<0.001
22	15	−1	0.0241	0.78	<0.001
23	23	−13	0.0287	0.74	<0.001

Regression equation: $y = a + bx$ Variables: $x = L/J$ $y = HCO_3$
HCO_3 = concentration HCO_3^- ($mg.l^{-1} = g.m^{-3}$)
other symbols like in Table 3

Table 5 Results of correlation and regression analysis of relation $Ca = f(L/J)$

Population	n	a	b	r	p
1	22	6.5	0.00182	0.905	<0.001
4	10	42	0.0238	0.521	0.12
5	11	(46)	(0.0171)	0.251	0.44
6	26	49	0.00833	0.285	0.15
7	9	15	0.0103	0.720	0.07
8	12	50	0.0263	0.390	0.18
15	9	28	0.00154	0.478	0.20
16	21	8	0.000351	0.579	<0.001
17	17	7	0.00149	0.651	0.005
18	6	(19)	(0.000531)	0.364	0.48
19	10	8	0.00808	0.850	0.12
20	11			−0.21*	
21	8	−32	0.0216	0.871	0.12
22	15	5	0.00672	0.633	0.011
23	23	3	0.00806	0.633	<0.001

Regression equation: $y = a + bx$ Variables: $x = L/J$ $y = Ca$
Ca = concentration Ca^{2+} ($mg.l^{-1} = g.m^{-3}$)
other symbols like in Table 3

10. the Bystrica Member and the Vlára Paleogene facies in the Biele Karpaty Unit (n = 10),
Bohemian Cretaceous Basin:
11. Middle-Turonian and Coniacian sandstones in the Lužické hory Mts. (n = 8),
Permian-Carboniferous formations in Lower-Silesian and Krkonoše piedmont Basins:
12. Carboniferous sediments in the SW part of the Lower-Silesian Basin (n = 8),
13. paleovolcanics of the Lower-Silesian Basin (n = 8),
14. Autunian sediments of the Lower-Silesian Basin (n = 5),
15. Carboniferous and Lower Autunian of the Krkonoše piedmont Basin (n = 9),
Crystalline complexes in area of Krušné hory Mts.
16. metamorphic rocks of the Nejdecká vrchovina upland (n = 21),
17. "mountain type" granites in the Nejdecká vrchovina upland (n = 17),
Crystalline complexes in area of Lugica
18. crystalline complexes of the Frýdlantská pahorkatina upland (n = 6),
19. crystalline complexes of the Ještědský hřbet Mts. (n = 10),
20. granites in the Jizerské hory Mts. (n = 11),
21. crystalline complexes of the western Krkonoše Mts. (n = 8),
22. crystalline complexes of the eastern Krkonoše Mts. (joined populations 21—22, n = 23).

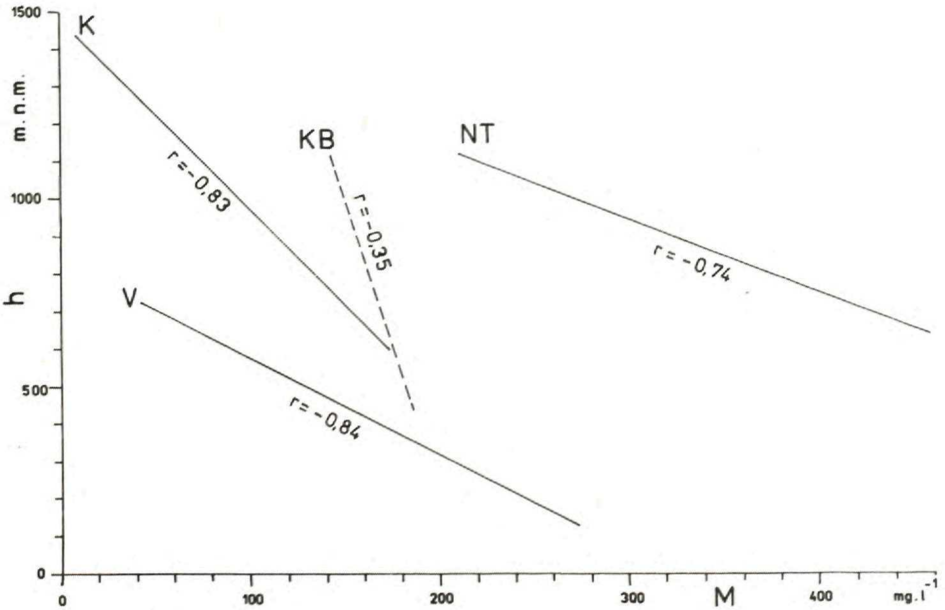

Fig. 9 Summarizing graph of regression lines M = f(h) of regions studied.

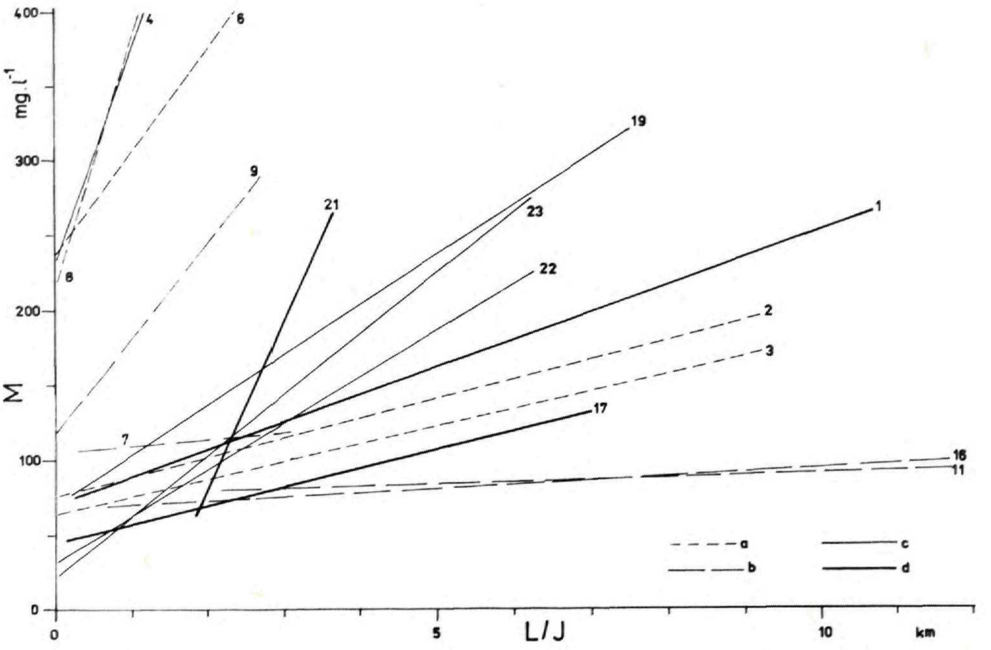

Fig. 10 Summarizing graph of regression lines $HCO_3 = f(L/J)$ in regions studied. a – r = = 0.30 – 0.50, b – r = 0.50 – 0.65, c – r = 0.65 – 0.80, d – r = > 0.80.

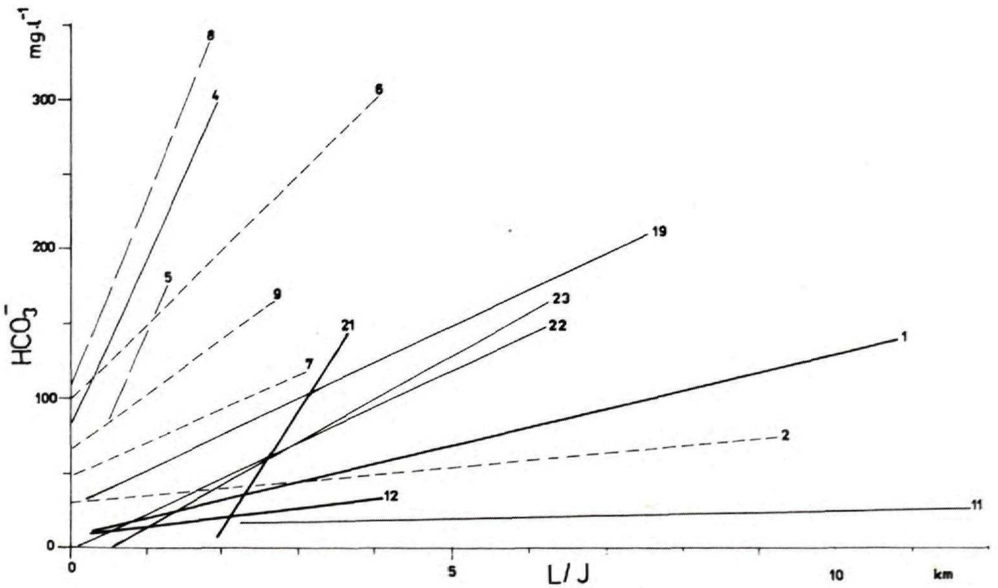

Fig. 11 Summarizing graph of regression lines $HCO_3 = f(L/J)$ in regions studied. For explanations see Fig. 10.

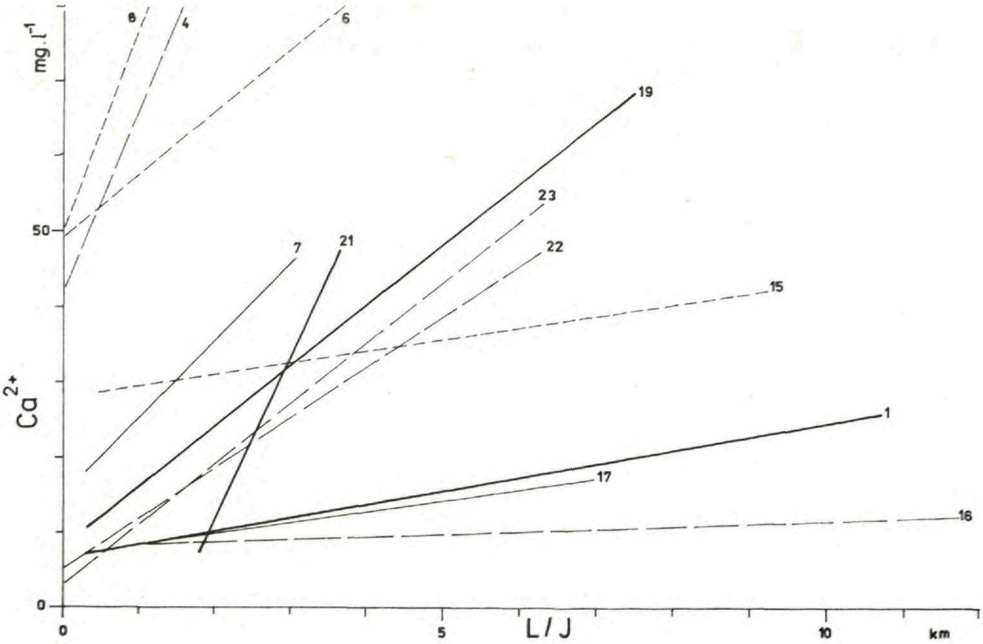

Fig. 12 Summarizing graph of regression lines Ca = f(L/J) in regions studied. For explanations see Fig. 10.

Analysed populations of data

The populations comprise data on 216 springs in the Carpathian system and 126 springs in the Bohemian Massif. Selected characteristics of the 23 populations given in Table 6 complement brief characteristics of individual regions and populations. A detailed evaluation of populations 2,3 and 9—14 was done by JETEL—RYBÁŘOVÁ (1983b), populations 4—7 and 15—23 were evaluated in a report by JETEL—RYBÁŘOVÁ (1985a).

The region characterized by population 2 and 3 is described in detail by JETEL and RYBÁŘOVÁ (1975, 1983a). It is a mountain area composed of dominant flysch noncalcareous glauconite sandstones alternating with non-calcareous claystones (population 2) or with dominant non-calcareous sandstones (population 3). The dissected mountain relief is typical also for the region characterized by the populations 4 (calcareous sandstones with organic carbonate detritus, claystones), 5 (sandstones, conglomerates, siltstones), 6 (sandstones, conglomerates, claystones), 7 (glauconite quartz sandstones), 8 (calcareous claystones with sporadic sandstone layers), 9 (variably calcareous sandstones with claystones) and 10 (calcareous sandstones, calcareous claystones).

Steep slopes alternate with flat parts in the region of the population 11 (quartz sandstones). The region of populations 12 (sandstones, arcoses, conglomerates, siltstones, claystones), 13 (paleovolcanics) and 14 (sandstones, siltstones, claystones) was described by JETEL (1979), the region 15 (sandstones and siltstones with limestone intercalations) by KRÁSNÝ (1976). JETEL (1972) also presented hydrogeologic characteristics of regions 16 (peneplain with steep slopes in valleys — micaschists, phyllites, quartzites) and 17 (granites). The flat relief of the region 18 (granites and metamorphic rocks) is in a contrast to the conspicuous morphology of the mountain ridge in the region 19 (epizonal metamorphic rocks) and to the mountain relief of the regions 20 (granites), 21 (epizonal metamorphic rocks) and 22 (metamorphic rocks).

The individual populations studied show considerable differences in sample values of linear correlation coefficients, regression constants and regression coefficients.

Correlation closeness

Differences in correlation closeness are usually caused by objective conditions of circulation and formation of groundwater chemical composition, but sometimes they are due to the character of analysed data. Correlation of the variables studied is weakened by all kinds of deviations of the actual conditions from the simplified model accepted for quantitative study of the correlation. The correlation is weakened where in consequence of high chemical activity of rocks (mostly by high carbonate content) the dissolved solids content increases close to the equilibrium value corresponding to water saturation with the given component.

High carbonate content may be associated with unfavourable influence of variable dissolution rate of calcite w_i (cf. PLUMMER et al. 1978). Carbonate content, few data and inhomogeneity of the population evidently caused insignificance of correlations in populations 10, 14 and 15. Interesting is a comparatively distinct correlation in population 4 significant in spite of rather high $CaCO_3$ content in the flysch of Hostýn formation.

Weakened correlations may also be due to particular geomorphology of the region, mainly irregular and complicated slope profiles. The correlation is weakened when the slope dip in individual parts of the filtration path changes so irregularly and conspicuously that the first groundwater body level dip gets unconformable with the ground surface dip, and then it is difficult to determine it from level lines.

The model cannot be applied when springs are mostly fed by sources different from the descending flow in the near-surface zone. Ascending feeding or lateral afflux along fault- and fissure zones disturb the relation of the flow velocity to the slope dip, and the filtration length is not in accordance with the distance between the place of infiltration and the spring.

The relations studied may also be disturbed even if the purely descending feeding is preserved. It is so in case when the feeding length does not correspond to the average length of the slope above the spring; e. g. where the spring represents the issue of a local communication system restricted to a small section of the slope above the spring. The actual feeding length L is then markedly different from the length L_m derived from a map and the spring shows much lower M_i concentration than that corresponding to L_m (the L/J value is overestimated). During descendant feeding these relations may also be disturbed by feeding along a privilege hydraulic communication with a higher permeability than the average permeability of the near-surface zone, like an open fracture parallel to the first groundwater level dip, or a washed-out channel in slope deposits.

The character of the data treated causes weakening of calculated sample correlation if too few data are treated at a relatively low objective correlation closeness (at a low correlation coefficient in the general population) or if data are treated with a narrow variation range of some of the variables (cf. population 5 and its characteristics in Table 6).

Statistical inhomogeneity of data is most important. Some populations comprise data resulting from more-or-less synchronous sampling (in an equal situation of regime changes in chemical composition and groundwater flow) while other populations comprise data resulting from sampling in different times — i. e. at different periodical changes of hydrochemical and hydrodynamical conditions. In such cases the compilation of a new population of data resulting from simultaneous sampling in the entire region may be followed by increasing sample correlation coefficient. It may be illustrated with the relations in the Vsetín Member of the Magura Flysch. The results of the 1st and 2nd phases show that it is probably impossible to prove statistically significant relations of hydrochemical characteristics to L/J values in the pelite Vsetín Member because of high carbonate content and low permeability (JETEL—RYBÁŘOVÁ 1983b, 1985a). The examination of a new population of data on 12 water samples taken in several days on a relatively small area of 68 sqkm (JETEL 1985d) proved statistically significant relations to L/J for M, HCO_3^- and Ca^{2+} for thus formed population 8 (Tables 3—5). It follows that the time homogenization of data may increase the sample correlation coefficients in other regions as well.

Qualitative inhomogeneity — a compilation of the only population of data from regions of different geology, hydrogeology or geomorphology — may have a considerable influence. The sample correlation coefficients may then increase after a division of the data into more populations with a higher homogeneity. For example: the sample correlation coefficients increased after a revision of a model population of data from the Vihorlat and Popričný Mts. (in contrast to population 1 the original population also comprised data on springs in Paleogene sandstones). Another example: the division of the population of data on the Soláň Formation s. l. from the 1st phase (JETEL—RYBÁŘOVÁ 1983b) into populations 4, 5, and 7 corresponding to different lithostratigraphic members in a new division system. Extremely weak correlations in the population 18 may be caused by its great inhomogeneity and few data. The mode of selecting slope

Table 6 Selected characteristics of populations studied

Population	n	$\bar{x}$	x_{min}	x_{max}	$\bar{M}$	M_{min}	M_{max}
1	22	3796	320	10667	140	60	264
2	71	1958	100	9200	101	26	460
3	30	1343			79	20	410
4	10	1068	280	1880	382	148	603
5	11	723	500	1200	257	129	385
6	26	1077	190	4000	308	80	542
7	9	963	300	3050	155	63	313
8	12	804	240	1800	372	104	610
9	15	773	150	2500	165	50	290
10	10	2905			463	270	690
11	8	19475	2200	44800	105	50	160
12	8	1868	440	4100	138	70	280
15	9	4665	430	9140	254	165	405
16	21	8672	625	33600	90	34	205
17	17	2631	250	7000	77	43	169
18	6	14090	1500	29630	174	48	355
19	10	2696	310	7410	160	79	320
20	11	2240	750	10610	81	56	122
21	8	2532	1830	3640	138	55	262
22	15	1974	150	6250	93	20	237
23	23	2168	150	6250	109	20	262

n = number of data
$\bar{x}$, x_{min}, x_{max} = arithmetic mean, minimum and maximum L/J values
$\bar{M}$, M_{min}, M_{max} = arithmetic mean, minimum and maximum T. D. S. values (mg . l^{-1})

sections for measurements of J and L values also influences correlation in a population, since the parameters determination is not always unambiguous. The determination of the dip J has been already discussed. In the determination of the length L it is necessary to consider the average effective length of water transport from the infiltration moment to the spring. When infiltration proceeds along the entire lateral descending path (Fig. 1), then the half distance between the highest point of the infiltration area water divide and the spring measured along the course of water advance to the spring, is regarded as the optimal approximation of the effective length of filtration. These factors affect variably the results of the analysis. A relatively low chemical activity of rocks (mostly non-alterated effusive rocks of andesite type with low contents of $CaCO_3$ sulphates, sulphides in the near-surface zone and a rather uniform relief with monotonous slope course represent favourable conditions for high values of sample correlation coefficients in the neovolcanic region of the Vihorlat and Popričný Mts. A wide range of M_i concentrations, J and L/J values, and altitudes h, represents another favourable factors.

No statistically significant correlations with L/J values were proved for populations 10, 13, 14, 18 and 20. The significance of correlations in population 5 and 15 is very low as well. We have already indicated the causes of insignificance for population 5, 10, 14, 15 and 18. Populations 13 and 20 concern regions of dominant sulphate waters with low T. D. S. Sulphates are not produced by quasi-linear increase of concentration in the near-surface zone in accordance with the model accepted but they mostly come from acid precipitation (the region of the Jizerské hory Mts., represented by population 20, is a typical area of intense anthropogenic acidification). Information on the sulphate concentration after transition through the soil zone is missing. Sulphates partly originate from rapidly decomposing sulphides, irregularly distributed in the rock environment. Small extent of populations and a narrow range of concentrations also play a certain role here. High proportion of sulphate waters is indicated by the absence of correlations between HCO_3 and L/J in populations 3, 16 and 17, and by a low correlation coefficient in population 2.

Regression constants and regression coefficients

The value of the constant a_i in equations of type (32) reflects the composition of precipitation waters and its changes during vertical descent through the soil and the unsaturated zone. The constant represents the average concentration in water entering the lateral descending flow in the first groundwater body. Calculated values of a_i for linear relations of M, HCO_3 and Ca to the values of L/J in individual populations with statistically significant correlations vary in the following intervals:

a(M): -149 to 239 mg . l^{-1} (median 71 mg . l^{-1})

a(HCO_3): -148 to 108 mg . l^{-1} (median 26 mg . l^{-1})

a(Ca): -32 to 50 mg . l^{-1} (median 8 mg . l^{-1})

The lowest (negative) a_i values (Krkonoše Mts.) are indicative of extremely low concentrations in unsaturated zone. In population 21 it is also due to the absence of springs with L/J < 1830 m. Differences in a_i values reflect differences in climate, biologic activity of soil zone and in carbonate contents. The flysch formations show striking differences between populations 7 and 11 on the one hand and populations 4, 6, 8 on the other.

A comparison of equations (25) and (26) with the equation (32) shows that regression coefficients b_i correspond to C_1/C_2 ratio in the equation (24) and reflect differences in velocities w_i and in hydraulic properties of the near-surface zone (k, m_A/m_e). In populations with statistically significant relations to L/J the regression coefficients are in the following intervals: b(M): 0.0014—0.159 g . m^{-4} (median 0.031 g . m^{-4})

b(HCO_3): 0.0010—0.126 g . m^{-4} (median 0.026 g . m^{-4})

b(Ca): 0.00035—0,026 g . m^{-4} (median 0.0082 g . m^{-4}).

Differences in the course of observed regression relations to the parameter L/J are shown in Fig. 10—12. In Fig. 10 four groups of regression lines M = f (L/J) may be distinguished. The first group comprises populations with high a(M) and b(M) values. They are populations 4, 6, and 8, i. e. flysch regions of the Hostýnské vrchy Mts. with high Ca-content in rocks, and a dissected relief. The average annual total precipitation is about 750—900 mm at average annual temperatures about 6—8 °C. The second group of lines with lower a(M) and b(M) values is represented by regions 19, 22 and 23 — Ještěd and Krkonoše Mts., i. e. mountain regions with silicatogenic waters and steep slopes. The average total precipitation is higher there (900—1500 mm), the average temperatures (0—6 °C) are lower than in the first group.

The third group comprises regions 1, 2, 3 and 17 differing in lower regression coefficients from the second group. They are mostly regions of silicatogenic waters and dissected relief (Vihorlat and Popričný Mts., non-calcareous flysch formations of Moravsko-Slezské Beskydy Mts., granites in Krušné hory Mts.). Except in the Vihorlat and Popričný Mts. (700—1000 mm, 6—8 °C) the average total precipitation (900—1500 mm) and average temperatures (2—7 °C) are analogous with those of the second group.

Populations 11 and 16 representing regions of mostly silicatogenic waters and a relatively smooth relief (sandstones of Lužické hory Mts., metamorphic rocks of plateaus in Krušné hory Mts.) show extremely low b(M) values (precipitation 700—1000 mm, temperatures about 4—7 °C). In Fig. 10 the regression lines of populations 7, 9, and 21 represent a transition between individual groups in accordance with the type of relief, climatic conditions and Ca- content of rocks.

Graphs $HCO_3 = f(L/J)$ in Fig. 11 show similar groups (group I: populations 4, 5, 8; II: 7, 19, 22, 23; III: 1, 2, 12; IV: 11, transitional position: 6, 9, 21) as well as graphs $Ca = f(L/J)$ in Fig. 12 (I: 4, 8; II: 19, 22, 23; III: 1, 15, 17; IV: 16, transitional position: 6, 7, 21). The regression constant values reflect climatic differences and Ca-content in rocks, and the regression coefficient seems to be — besides other factors — controlled by the dissection of relief. Interpretations of regression coefficient values will be discussed below.

Relations between T. D. S. and altitude

The relations between T. D. S. and the spring altitude h were studied in 4 regions: Vihorlat-Popričný Mts., Kysucké Beskydy Mts. (population 9), Krkonoše Mts. (population 22) and dolomites on NE slopes of the Nízke Tatry Mts. The population of data from the Nízke Tatry Mts. was additionally constructed of data presented as points in the graph $M = f(h)$ by GAZDA and HANZEL (1980).

The results of analysis of the $M = f(h)$ are given in Table 2 and Fig. 9. High values of T. D. S. of waters from dolomites of the Nízke Tatry Mts. (regression line shifted along axis M) are indicative of a conspicuous hydrochemical difference between carbonate complexes and other rock types studied.

Correlation between T. D. S. and altitude h integrates the effects of several phenomena — the effects of differences in the intensity of feeding with precipitation water, the influence of differences in average slope dips, in average temperature affecting the chemical reaction velocities, the effects of differences in the soil zone biochemical activity, controlled by differences in temperature, vegetation and soils. Matter of relations between T. D. S. of water and spring altitudes was already pointed out by GAZDA—HANZEL (1980) emphasizing the influence of differences in biochemical soil activity upon differences in partial pressure of CO_2 (i. e. one of the main factors controlling the formation of water chemical composition in rocks).

Possible extension of number of examined characteristics

For the continuation of investigations it will be necessary to extend the number of examined characteristics with concentrations of other components, reliably dated.

The so far examined components HCO_3^- and Ca^{2+} are not quite suitable for the study of considered relations, since besides by interaction with rock their concentrations are also controlled by other processes (HCO_3^- is mostly influenced by biological processes and Ca^{2+} besides biological fixation also by ion exchange).

The relations should be examined for Na^+ because it is a very stable component of a solution (it is practically non-fixed). Na^+ exhibit a prominent relation to the L/J path when hydrolysis of silicates (mainly feldspars) is the main mineralizing process. The exchange velocity is only partly controlled by pH. A relatively low Na^+ concentration in descending spring water (considerable analytical inaccuracy, too narrow range of concentrations observed) is quite a problem. Some relations may also be expected between Mg^{2+} and L/J.

As for the selection of indirect hydrodynamical characteristics, it would be interesting to examine possible relations between hydrochemical characteristics and quantitative characteristics describing the depletion curves of springs (cf. KULLMAN—PETRÁŠ 1977; KULLMAN 1980).

Possible practical application of results

The results of quantitative study of relations between hydrochemical and hydrodynamical parameters may practically be applied in the study of hydraulic properties of a rock environment (JETEL—RYBÁŘOVÁ 1983b, 1985a, b; JETEL 1985b), in the estimation of velocities of geochemical processes and in the study of anthropogenic changes of geochemical characteristics and processes in natural environment (JETEL 1987a).

Indirect estimation of near-surface zone permeability

When in the equation (26), expressing the resulting M_i concentration of component i in descending spring water corresponding to the model given in Fig. 1, the increase of ΔM_i concentration acquired on the filtration length L is expressed by the equation (25), then the resulting equation is as follows:

$$M_i = M_{oi} + \frac{w_i}{k} \cdot \frac{m_A}{m_e} \cdot \frac{L}{J} \tag{46}$$

A comparison of this equation to the equation of type (32)

$$M_i = a_i + b_i \, L/J \tag{47}$$

shows that in terms of the model accepted the value of constant a_i corresponds to the initial M_{oi} concentration value (it is its statistical estimation). Then the empirically determined sample regression coefficient b_i is a statistical estimation of the average value of the coefficient in the second term on the right side of the expression (46), i. e.

$$b_i = \frac{w_i}{k} \cdot \frac{m_A}{m_e} \tag{48}$$

At the constant velocity of the transition of component i from rock to water (w_i) and at the constant m_A/m_e ratio the reciprocal value of regression coefficient b_i characterizes thus the average permeability of the rock environment through which water flows to springs, because a formal modification of the equation (48) results in the relation

$$k = \frac{w_i}{b_i} \cdot \frac{m_A}{m_e} = \frac{1}{b_i} \cdot \frac{w_i m_A}{m_e} \tag{49}$$

The equation enables the determination of the average hydraulic conductivity of the near-surface zone in the feeding area of descending springs in a certain more-or-less homogeneous region according to the value of the regression coefficient b_i of an equation of (47) type, resulting from statistical analysis of data about chemical composition of waters and morphometrical position of springs. It is the starting equation of a new method of indirect estimation of the hydraulic conductivity from hydrochemical and geomorphometrical data (Jetel—Rybářová 1985a; Jetel 1985b).

Practical application of the method is only possible at knowledge or reliable estimation of the values of interaction velocity w_i and m_A/m_e.

Estimation of average interaction velocity

The equation (48) shows that the average velocity $w_i = dq/dt$ — under the conditions of the model accepted — is directly proportional to the regression coefficient b_i according to the relation

$$w_i = b_i \, . \, k \, . \, m_e/m_A \tag{50}$$

Since the hydrochemical variables were substituted into equations of type (47) in mass concentrations ($mg.l^{-1}$, i.e. $g.m^{-3}$), the coefficients b_i are expressed in $g.m^{-4}$. Then the resulting interaction velocity is expressed in $g.m^{-3}.s^{-1}$. Thus the molar concentration dq ($mol.m^{-3}$) from equation (9) is replaced by mass concentration in $g.m^{-3}$.

The concrete application of the results may be demonstrated upon data about the relation $M = f(L/J)$ in the model population 1. The values of input data for equation (50) can be determined from the results of hydrogeological exploration (BAJO et al. 1976, 1983) and by analogy according to table data. The average chemically effective porosity of andesites in the near-surface zone is estimated to $m_e = 0.01$ from Juhász's (1976) graph of average andesite porosity change with increasing depth, as well as the average filtration cross-section effectiveness, proportional to porosity, approximately to $m_A = 0.004$. So for the value of the m_e/m_A ratio the approximate value 2.5 will be accepted. In practical application of the equations (47)—(57) it is unnecessary to know the actual values of m_e and m_A; only the average values of the m_e/m_A ratio should be estimated (i.e. how many times the chemically effective porosity exceeds the "hydrodynamically" effective porosity m_A). The average hydraulic conductivity of andesites in tested intervals of wells ($k = 8 \times 10^{-6}\ m.s^{-1}$, BAJO et al. 1983) will be substituted in equation (50). After the substitution of the values of m_e/m_A and k mentioned, together with the regression coefficient $b(M) = 0.0182\ gm^{-4}$ from equation (41) calculated for springs of the respective region, the estimate $w(M) = 3.6 \times 10^{-7}\ g.m^{-3}.s^{-1}$ will result from equation (50).

We can similarly estimate the average interaction velocities w(M), $w(HCO_3)$ and w(Ca) for other regions studied with data on the near-surface zone permeability. If we accept $m_e/m_A = 2.5$ for most cases and $m_e/m_A = 5$ for a very low permeability, the resulting estimates — after the elimination of extreme and doubtful values — will have the following range:

$$w(M) = 5.8 \times 10^{-8} - 7.1 \times 10^{-7}\ g.m^{-3}.s^{-1}$$

$$\text{with median } w(M) = 2 \times 10^{-7}\ g.m^{-3}.s^{-1}$$

$$w(HCO_3) = 4.5 \times 10^{-8} - 5.9 \times 10^{-7}\ g.m^{-3}.s^{-1}$$

$$\text{with median } w(HCO_3) = 1 \times 10^{-7}\ g.m^{-3}.s^{-1}$$

$$w(Ca) = 8.4 \times 10^{-9} - 1.2 \times 10^{-7}\ g.m^{-3}.s^{-1}$$

$$\text{with median } w(Ca) = 2 \times 10^{-8}\ g.m^{-3}.s^{-1}$$

The ranges and medians of the individual components only characterize the populations exhibiting a significant correlation between the respective component i and the parameter L/J.

The values of hydraulic conductivity derived from wells and substituted into equation (50) may be considerably overestimated in comparison to actual effective values of hydraulic conductivity of the near-surface zone in slopes

(JETEL—KULLMAN 1989), so the actual values of w_i will be lower in average as well. If we also consider the estimate of m_e/m_A as approximate, then the w_i values quoted may evidently be regarded as purely preliminary estimates. However, the values derived from calculations of the outflow velocities of the given components on the basis of mass balance (PAČES 1973; JETEL 1987a) may indicate the lower limit of possible range of w_i velocities.

We have accepted a simplified presumption (13) of a constant velocity dq/dt for the environment examined. Generally, however, this velocity is inconstant because it is a function of water composition and properties of minerals surfaces (PAČES 1983a, b). So velocities w_i resulting from equation (50) should be regarded as average effective velocities of geochemical interaction in a given environment. The data on the solution of rock minerals under natural conditions (e. g. FRITZ 1975; PETROVIĆ 1976; PALCIAUSKAS—DOMENICO 1976; PAČES 1973, 1983a, b) show that it is very difficult to derive theoretically the w_i velocities on the basis of deterministic models for real conditions, and some input data can even not be measured at all. A confrontation of estimates from equation (50) with theoretical values w_i will enable the precision of permeability estimations according to the relation (49), and offer an empirical criterion of reliability of theoretical determination of interaction velocities. It will also enable the precision of estimation of specific surface and other unmeasurable parameters under real rock conditions.

Practice of near-surface zone permeability estimation

The indirect estimation of the near-surface zone permeability estimation proceeds as follows:

The sample regression coefficient b_i in equation (47) for the examined component i showing a statistically significant relation of concentration M_i to parameters L/J is determined by correlation and regression analysis of statistical relations between favourable hydrochemical characteristics and geomorphometric parameter L/J of descending springs in a geologically quasi-homogeneous region. The component i may also represent the T. D. S. content. The analysis also offers probable estimation of possible errors of values b_i as a basis for evaluation of reliability of other parameters (k, w_i) estimation. For the estimation of the mean hydraulic conductivity of the near-surface zone in the region studied, the equation (49) will be used. With the determined b_i value also the estimation of expected m_e/m_A value and the average interaction velocity rate w_i value (or its expected limits) will be substituted in the equation (49).

For a wider application of the practice sugggested a permanent precision of data on actual distribution of average velocities w_i in relation to concrete geochemical and hydrogeological conditions — by the equation (50) where the average permeability of slope sections of near-surface zone will reliably be proved by hydrodynamical tests in holes, and by theoretical derivation of interaction velocities on the basis of chemical kinetics under concrete conditions — will be necessary.

For the application of the method it is inevitable to have sufficient data on chemical composition of descending springs water, suitable for the model accepted. The method is useful for regions of dissected relief. The results of indirect estimation of permeability should be systematically confronted with the results of other methods and the conclusions should contribute to further development and precision of the method.

Monitoring geochemical processes

Since regression equations of the type (47) give objective characteristics of the present state of the formation of groundwater chemical composition near the ground surface, they may possibly be used as a basis for monitoring of anthropogenic changes in the geochemical state of the landscape (JETEL 1987a). Changes of quantitative parameters of equations (47) should be monitored after repeated synchronous sampling in sufficiently long time lags. GAZDA, BODIŠ and VRANA (1983) presented data, showing that especially the values of constants a_i may be a sensible indicator: their changes in time may signalize anthropogenic changes of processes in soil cover.

Conclusions

1. The study of quantitative relations between hydrochemical and hydrodynamical characteristics resulted in theoretical derivation and empirical affirmation of basic relations between groundwater chemical composition and hydrodynamical conditions at lateral descending flow through the near-surface zone which is most frequently the main aquifer in fractured rock massifs.

2. Concrete manifestations of the laws derived were quantitatively examined by correlation and regression analysis of data on chemical composition of waters and morphometric position of 342 descending springs in 23 selected regions in the Carpathians and Bohemian Massif.

3. The main practical application of the results consists in the proposal of quite a new method of indirect estimation of the average permeability of the near-surface zone in the region studied, based on hydrochemical and geomorphometrical data.

4. The results may also be applied in the estimation of geochemical water-rock interaction rates and in monitoring geochemical processes in respect of anthropogenic influence.

5. The results of investigations stimulate further hydrogeological, geochemical and geohydraulic researches. It will now be useful to

a) continue quantitative examination of the relations studied in other regions,

b) extend the number of the variables studied (Na^+, Mg^{2+}, parameters of depletion curves of the springs, a. o.),

c) increase homogeneity of populations studied, by deeper analyses of hydrogeological conditions of individual springs as a basis for the formation of more homogeneous populations (qualitative homogenization) and by the formation of new populations of data from synchronous sampling (time homogenization),

d) study possible regularities of changes in quantitative relations by comparing the results from particular synchronous sampling, characterizing different states of periodically changing processes,

e) precise the estimation of interaction rates w_i at the precision of data on the near-surface zone permeability according to hydrodynamic tests in holes,

f) confront the estimates of velocities w_i from regression equations with the theoretical rates of the dissolution of minerals,

g) confront the estimates of the hydraulic conductivity of the near-surface zone according to equation (49) with the results of other methods, mainly of hydrodynamic tests in holes and precise thus the suggested method of indirect estimation of permeability.

Main symbols

a, a_i	— locating regression constant
b, b_i	— regression coefficient
f(x)	— function of argument x
h	— spring altitude (metres)
H_r	— internal relative information entropy of chemical composition of water (Jetel 1975)
i	— index specifying the component examined
J	— piezometric gradient, average dip of ground surface above spring
k	— hydraulic conductivity ($m \cdot s^{-1}$)
L	— filtration length (m)
L_0	— linear distance between profiles considered, measured in direction of flow
L/J	— reduced filtration length (m)
m_e	— chemically effective porosity (–)
m_A	— filtration cross-section effectiveness ("effective areal porosity") (–)
M	— total dissolved solids (T. D. S.) ($mg \cdot l^{-1} = g \cdot m^{-3}$)
M_i	— component-i concentration in water ($mg \cdot l^{-1} = g \cdot m^{-3}$; in equation (9) in $mol \cdot m^{-3}$)
M_{io}	— initial concentration of i-component in water ($mg \cdot l^{-1} = g \cdot m^{-3}$)
n	— number of data
p	— statistic significance level (–)

P	— probability of existing correlation in general population (P = 1 − p)
q	— amount of i-component, exchanged between volume unit of rock and water (mol . m^{-3}; in equation (23) amount of i-component in g . m^{-3})
Q	— volume discharge ($m^3 . s^{-1}$)
r	— linear correlation coefficient
R	— Spearman's coefficient of rank correlation
t_r	— water residence time in rock (s)
t	— time (s)
t_t	— transport time of tracer over distance L_0 (s)
u	— effective flow velocity along axis x (m . s^{-1})
v	— darcian velocity (specific flux) (m . s^{-1})
w, w_i	— i-component transition rate to solution from rock volume unit (interaction rate) (g . $m^{-3}s^{-1}$ or mol . $m^{-3}s^{-1}$)
w(Ca), w(HCO_3), w(M)	— interaction rate with the respective component (Ca^{2+}, HCO_3^-, M)
x	— spatial coordinate parallel to flow direction, independent variable
y	— dependent variable

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VLADIMÍR DOVINA

Underground runoff from crystalline complexes of West Carpathians — results of evaluation and their possible application on solution of basical hydrogeological problems

Abstract. Presented are results of evaluating the udnerground runoff from crystalline complexes of the West Carpathians Mts. The author gives brief geological and hydrogeological characteristics of the area studied and a brief information on the existing data about underground runoff. Most attention is paid to the evaluation and generalization of the data about underground runoff from both the characteristic types of rock environments and from single crystalline complexes. Possible application of the data obtained is suggested.

Introduction

The underground runoff is decising in the evaluation of permeability and hydrogeologic character of the West Carpathian crystalline areas. The study of underground runoff in relation to geological-tectonical structure, to hydrogeologic, geomorphologic and hydrometeorologic conditions results in data about basical hydrogeological laws and enables the solution of some basical problems.

Brief geological and hydrogeological characteristics of the West Carpathian crystalline areas

The geologic structure of the West Carpathian crystalline complexes is variable and tectonically complicated. The crystalline complexes only crop out in the Inner West Carpathians. They form the Tatricum ("cores" of core mountain ranges), the most parts of the Veporicum and the Gemericum. In the Outer West Carpathians in the Flysch- and Klippen Belts the crystalline rocks only occur in the form of "exotic pebbles".

Crystalline complexes of the West Carpathians consist of two geologic complexes (Fig. 1), namely crystalline schists (metamorphic rocks) and granitoid rocks (magmatites).

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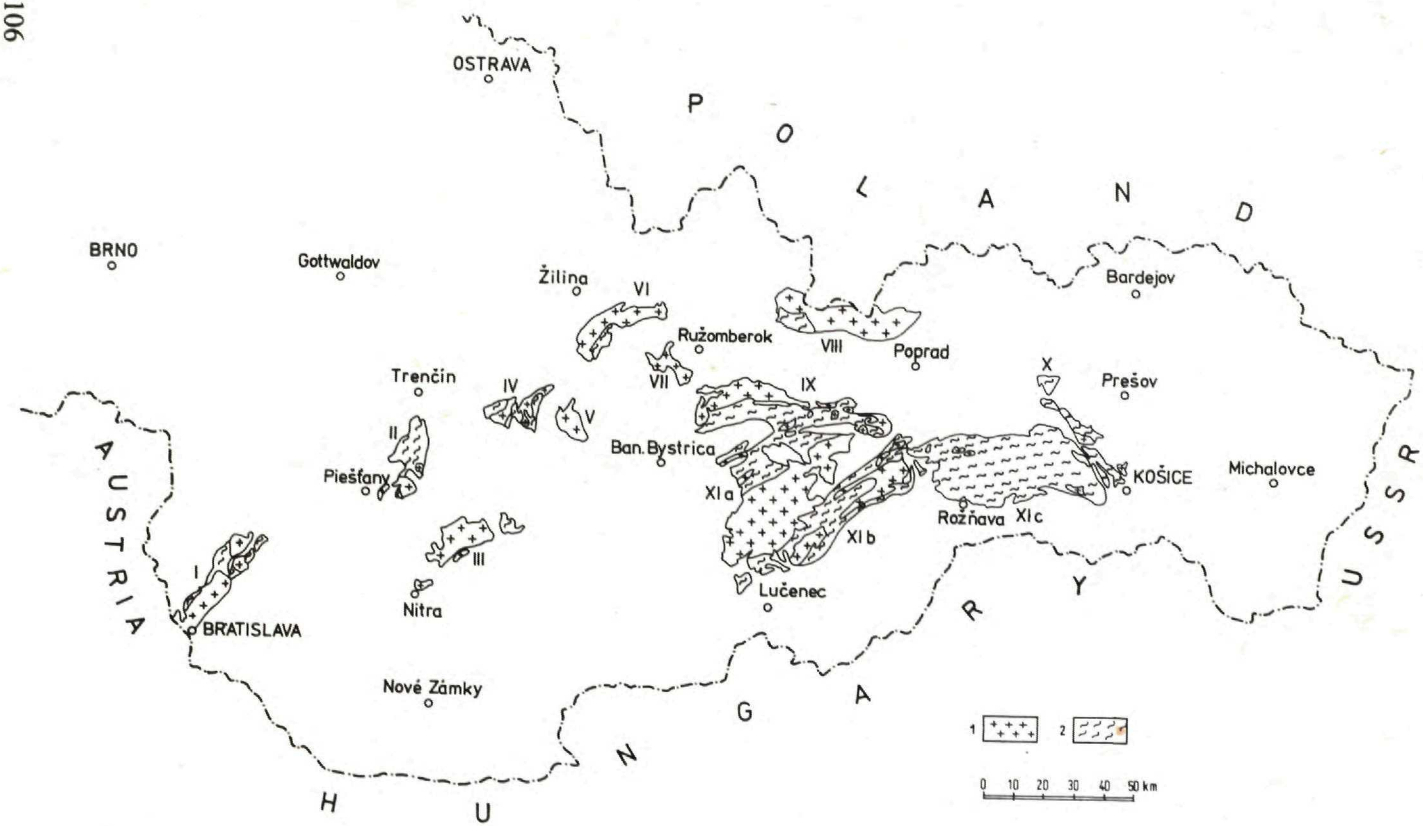

Fig. 1 Distribution of crystalline complexes is West Carpathians (accord. to Geological Map of CSSR 1 : 1 000 000) Fatra-Tatra region: I — Malé Karpaty Mts., II — Považský Inovec Mts., III — Tríbeč Mts., IV — Strážovské vrchy hills (Suchý, Malá Magura), V — Žiar Mts., VI — Malá Fatra Mts., VII — Veľká Fatra Mts., VIII — Western and Eastern Tatra Mts., IX — Nízke Tatry (Low Tatra) Mts., X — Branisko Mts., Slovenské rudohorie Mts. region: XI a — Veporské vrchy hills, XI b — Stolické vrchy hills, XI c — Volovské vrchy hills, XI d — Čierna hora Mts., Geologic characteristics: 1 — granitoid rocks, 2 — crystalline schists.

Crystalline complexes of the Tatricum comprise crystalline complexes of the Malé Karpaty Mts., Považský Inovec Mts., Tribeč Mts., Strážovské vrchy Mts., Žiar Mts., Malá and Veľká Fatra Mts., Žiar Mts., the Západné and Vysoké Tatry Mts. (Western and High Tatra), the western (Ďumbier) part of the Nízke Tatry (Low Tatra) Mts. and northern part of Branisko Mts. Crystalline complexes of the Veporicum comprise crystalline complexes in the eastern part of the Branisko Mts., crystalline complexes of the Veporské vrchy and Stolické vrchy hills in the Slovenské rudohorie Mts., and crystalline complexes of the Čierna hora Mts. Crystalline complexes of the Gemericum form the Volovské vrchy hills of the Slovenské rudohorie Mts. In the West Carpathians the crystalline complexes also crop out in small occurrences in the areas of Sklené Teplice, Pliešovce, Lieskovec, Ábelová, Zemplín island.

The geologic structure of crystalline complexes of the West Carpathians is reflected also in their hydrogeologic conditions.

Fissure permeability is dominant in the rock environment of crystalline complexes of the West Carpathians. In granitoid rocks are more favourable conditions for accumulation and circulation of groundwater than in crystalline schists. Most groundwater springs range up to $1.0\,\mathrm{l.s^{-1}}$ in yields. Springs with yields 1.0—$5.0\,\mathrm{l.s^{-1}}$ and higher are associated with areas of broken crystalline rocks and areas affected by intense fault tectonics. In some areas of West Carpathian crystalline complexes — in respect of hydrogeology — significant is the cooperation of crystalline rock massif with hydrogeologically more favourable rock complexes, mainly Mesozoic limestones and dolomites, Quaternary glacigenic or also glacifluvial sediments.

Existing data on underground runoff from areas consisting of crystalline complexes of West Carpathians

The first information about underground runoff of Slovakia was presented by O. Dub (1954). According to Dub (1954) the minimum specific runoff from crystalline complexes of single mountain ranges is 0.3—$3.0\,\mathrm{l.s^{-1}.km^{-2}}$, in the Veľká Fatra Mts. 3—$4\,\mathrm{l.s^{-1}.km^{-2}}$, in Western and High Tatra 4—$5\,\mathrm{l.s^{-1}.km^{-2}}$, and more, in the Nízke Tatra Mts 3—$5\,\mathrm{l.s^{-1}.km^{-2}}$ and more.

Kullman (1965) evaluated the influence of geologic conditions upon underground runoff and characterized the crystalline complexes according to 355 days water by specific groundwater runoff 1.0—$2.5\,\mathrm{l.s^{-1}.km^{-2}}$. Basing on the evaluation of specific runoff in the river basin of the Bacúšsky potok (5.3—$11.0\,\mathrm{l.s^{-1}.km^{-2}}$) and Štiavnička ($6.1$—$19.1\,\mathrm{l.s^{-1}.km^{-2}}$), Kullman presumes possible drainage of groundwaters from crystalline complexes by Mesozoic formations, and possible utilization of the results for the solution of some basical hydrogeological problems.

In crystalline complexes of the Western Tatra Mts. the groundwater runoff was studied by Melioris (1971, 1973, 1980a, b) and Melioris-Tomlain (1970, 1973). The water balance method was applied in the study of underground runoff in the river basin of the Račkov potok in the hydrological year 1968 (specific underground runoff 11.31 $l.s^{-1}.km^{-2}$). the minimum specific underground runoff was evaluated in the river basin of the Račkov potok brook (5.63 $l.s^{-1}.km^{-2}$), Belá (4.97 $l.s^{-1}.km^{-2}$) and Smrečianka (8.80 $l.s^{-1}.km^{-2}$). High values of the minimum specific underground runoff indicate a great retention capability of granodiorite and crystalline-schist environment in these river basins. The great retention capacity is due to a great depth range of the unloading decompression zone and the weathering zone, and in the Smrečianka river basin also to other factors (MELIORIS l.c.). On the grounds of data by MATUŠKA (1978) the average specific underground runoff was calculated from the results of Foster's method (23.8—24.53 $l.s^{-1}.km^{-2}$), Kille's method (20.11—23.32 $l.s^{-1}.km^{-2}$) and Castany's method (9.65—11.74 $l.s^{-1}.km^{-2}$) for the Belá river basin (Podbanské) in hydrological years 1931—1974, 1941—1974, 1951—1974.

Hanzel—Gazda—Vaškovský (1984) calculated the average underground specific runoff 7.8 $l.s^{-1}.km^{-2}$ by the Foster's method and the minimum specific underground runoff 1.2—4.2 $l.s^{-1}.km^{-2}$ from granodiorites of crystalline complexes in the Vysoké Tatry (High Tatra) Mts. for the hydrological years 1977—1980.

HANZEL (1974) evaluated the minimum specific underground runoff in the Bystrá river basin (3.6—5.4 $l.s^{-1}.km^{-2}$) and Štiavnica river basin (2.8—10.2 $l.s^{-1}.km^{-2}$) in crystalline complexes of the northern Nízke Tatry Mts. (mostly granitoid rocks) during hydrological years 1970—1972. HANZEL (l.c.) regards the increased values of the minimum underground specific runoff as a result of the drainage effect of Mesozoic synclines of Konský Grúň and Trangoška.

Explorations in crystalline complexes of the West Carpathians, aimed at the determination of underground runoff on the Czechoslovak territory, resulted in data on average specific undergroud runoff 2—5 $l.s^{-1}.km^{-2}$, and 7—10 $l.s^{-1}.km^{-2}$ and more in the Vysoké Tatry Mts. crystalline complexes (KRÁSNÝ et al. 1981, 1982).

Some basical data on the underground runoff resulted from the regional prospecting hydrogeological exploration in the Malá Fatra Mts. crystalline complexes (ŠALAGOVÁ et al. 1983, partly BUJALKA et al. 1973, ŠALAGA et al. 1974), in the Branisko Mts. crystalline complexes (FRANKOVIČ et al. 1974) and in the Čierna hora Mts. crystalline complexes (FRANKOVIČ et al. (1981).

MELIORIS (1974, 1976) and FIDELLI—MELIORIS (1978) studied the methods of underground runoff in mountain regions and applied them in the West Carpathians.

Recently the underground runoff from crystalline complexes of the West Carpathians and of the Nízke Tatry Mts. was studied by DOVINA (1984) and DOVINA et al. (1985) during hydrogeological researches in these regions.

The results of evaluation of underground runoff from crystalline complexes in other regions may be compared.

In the platform crystalline complexes of the Bohemian Massif in contrast to the folded crystalline complexes of the West Carpathians the average specific underground runoff is 2—5 $l.s^{-1}.km^{-2}$. Higher values are characteristic of mountain areas, mainly top parts of the South Bohemian crystalline complexes in the Šumava Mts., Jizerské hory Mts., Krkonoše Mts. and the Hrubý Jeseník Mts. The values range from 5.0 to 15.5 $l.s^{-1}.km^{-2}$ (KRÁSNÝ et al. 1981, 1982). In Central and East European crystalline regions the average specific underground runoffs mostly range from 1 to 5 $l.s^{-1}.km^{-2}$, in South Carpathian crystalline areas 7—10 $l.s^{-1}.km^{-2}$ as well as in Big Caucasus (KONOPLJANCEV et al. 1981, 1982).

Underground runoff from crystalline complexes of West Carpathians

The data available were treated by hydrological methods to determine the underground runoff for the hydrological years 1971—1980 in crystalline complexes of the West Carpathians. The period 1971—1980 is an average period as for climate and hydrology. The present knowledge indicates that the methods of underground runoff determination do not always result in unambiguous and reliable data. The underground runoff should be determined by methods suitable for the single geologic-tectonical and structural-hydrogeological complexes.

In the West Carpathian crystalline regions the underground runoff was determined by three methods regarded as most suitable, namely:

a) FOSTER's (1948) method — as the genetical determination of underground runoff,

b) KILLE's (1970) method,

c) CASTANY's method (CASTANY—MARGAT—ALBINET—DELLAROZIÈRE—BOUILLIN 1970).

The minimum underground specific runoff was also determined. The detailed results are presented by Dovina (1984).

The data resulting from the KILLE's (1970) method were applied in the evaluation and generalization of information about average underground runoff values concerning the West Carpathian crystalline complexes. The KILLE's (1970) method enables the determination of the probable average value of underground runoff from the total runoff almost unambiguously and objectively. Documented long-term minimum underground runoff average values were applied in the determination of data about the minimum underground runoff in crystalline complexes of the West Carpathians. The values resulting from hydrological methods were evaluated in relation to geologic-tectonical and hydrogeological conditions and served as a basis for the evaluation of underground runoff from characteristic rock environments and from mountain ranges consisting of crystalline complexes of the West Carpathians.

Evaluation of underground runoff from rock environments of single types in West Carpathian crystalline regions

The underground runoff was evaluated according to basical rock types in selected river basins. It was measured systematically in hydrological years 1971—1980 (Table 1). On the grounds of the results and after the evaluation of further factors controlling the underground runoff the characteristic values of the average and minimum specific underground runoffs was determined for individual types of rock environments in crystalline complexes of the West Carpathians (Table 2).

In river basins consisting of granitoid rocks with eluvial and deluvial cover, the average specific underground runoff ranged from 2.11 to 6.19 $l.s^{-1}.km^{-2}$ and the minimum specific underground runoff varied between 0.74 and 3.31 $l.s^{-1}.km^{-2}$. Considering further factors controlling the underground runoff from granitoid rocks we can state that the documented average and minimum underground runoff in selected river basins reflect the hydrogeologic character of the rock environment.

Basing on the results and evaluation of hydrogeologic character of areas composed of granitoid rocks, and considering further factors, we can characterize the crystalline areas of the West Carpathians, consisting of granitoid rocks, by the values of the average specific underground runoff 2—6 $l.s^{-1}.km^{-2}$ and of the minimum specific underground runoff 0.5—3.5 $l.s^{-1}.km^{-2}$.

In some river basins of the area studied there are besides dominant granitoid rocks also crystalline schists, mostly mica schists, gneisses and migmatites. Granitoid rocks have geological influence upon underground runoff. In such river basins the average specific underground runoff ranged from 4.73 to 5.45 $l.s^{-1}.km^{-2}$ and the minimum specific underground runoff varied between 2.67 and 3.07 $l.s^{-1}.km^{-2}$.

Considering the decisive factors, hydrogeologic conditions and resulting data, we have determined the average value of spedific underground runoff 4—6 $l.s^{-1}.km^{-2}$ and the minimum specific underground runoff 2.0—3.5 $l.s^{-1}.km^{-2}$ for the West Carpathian crystalline areas composed of granitoid rocks and partly of crystalline schists. The values are preliminary, because they resulted from data on two river basins only.

In other crystalline areas of the West Carpathians, consisting of granitoid rocks, the underground runoff is controlled not only by these rocks and their tectonic deformation, weathering crust thickness and other factors, but also by Quaternary glacigenic and glacifluvial sediments and by Mesozoic formations in a tectonic position. In these areas the value of the average specific underground runoff ranging from 10.60 to 21.69 $l.s^{-1}.km^{-2}$ and the minimum specific underground runoff ranging from 5.66 and 11.02 $l.s^{-1}.km^{-2}$ were extremely high.

Table 1 Average and minimum specific underground runoff values from rock environments in selected river basins in crystalline complexes of West Carpathians in hydrological years 1971—1980

Characteristic rock environment	Stream Water-gauge station (Precipitation-gauge station)	River-basin area (km^2)	Average annual total precipitation (mm)	Specific underground runoff ($l.s^{-1}.km^{-2}$)	
				average	minimum
1	2	3	4	5	6
granitoid rocks	Bystrica Spariská (Kamzík)	7.25	670	2.28	0.99
	Bystrica Červený most (Kamzík)	23.65	670	2.11	0.74
	Kamenný potok Modra—Harmónia (Modra)	9.34	627	4.45	1.70
	Slatina Hriňová nad priehr. (Hriňová)	51.99	763	6.19	3.31
	Kriváň Píla (Budiná)	48.83	762	2.79	1.55
granitoid rocks, crystalline schists (smaller amount)	Čierny Hron Čierny Balog (Krám)	64.61	740	5.45	3.07
	Klenovecká Rimava Ráztočné (Hnúšťa)	67.36	750	4.73	2.67
granitoid rocks with Quaternary, mostly glacigenic and glacifluvial sediment cover, with Mesozoic carbonates in tectonic position	Kamenistý potok brook Podbanské (Podbanské)	10.30	932	19.34	7.11
	Belá Podbanské (Podbanské)	93.49	932	21.69	9.78
	Kôprový potok brook Kôprova dolina valley (Podbanské)	31.20	932	20.63	8.46
	Križianka Horáreň Hluchý (Jasná)	19.80	1314	17.51	11.02
	Zadná voda Kožiarka (Jasná)	16.45	1314	17.52	6.81

Table 1

Characteristic rock environment	Stream Water-gauge station (Precipitation-gauge station)	River--basin area (km^2)	Average annual total precipitation (mm)	Specific underground runoff ($l.s^{-1}.km^{-2}$)	
				average	minimum
1	2	3	4	5	6
granitoid rocks with Quaternary, mostly glacigenic and glacifluvial sediment cover, with Mesozoic carbonates in tectonic position	Bystrá Hájovňa pred Bystrou (Jasná)	11.10	1314	10.60	5.66
	Štiavnica Hájovňa pred Bystrou (Jasná)	14.33	1314	16.38	10.76
	Bystrička Kunerád	11.44	960	17.98	8.41
crystalline schists, (Volovské vrchy hills)	Rožňavský potok brook Rožňava (Rožňava)	41.80	727	3.37	1.91
	Súľovský potok brook Gemerská Poloma (Podsúľová)	57.38	854	3.96	1.35
	Ida Hýľov—Mexiko (Zlatá Idka)	34.06	841	6.86	2.96
	Bodva Nižný Medzev (Vyšný Medzev)	96.30	786	2.99	1.83
crystalline schists, granitoid rocks (smaller amount)	Čierny Hron Hronec (Krám)	239.41	750	6.21	3.73
	Kamenistý potok brook Hrončok (Krám)	48.86	740	7.55	4.60
	Rimavica Lehota n/Rimavicou (Lehota n/Rimavicou)	148.95	730	4.13	2.53
	Župkov potok brook Červená Skala (Švermovo)	2.83	867	5.12	2.69
	Stratenik Švermovo—Dlhá dolina valley (Švermovo)	5.27	867	8.01	4.36

Table 1

Characteristic rock environment	Stream Water-gauge station (Precipitation-gauge station)	River-basin area (km^2)	Average annual total precipitation (mm)	Specific underground runoff ($l.s^{-1}.km^{-2}$)	
				average	minimum
1	2	3	4	5	6
crystalline schists, granitoid rocks (smaller amount)	Pivovarský potok brook Martin (Bystrička)	9.05	743	6.64	3.20
crystalline schists of Mesozoic carbonates in tectonic position	Štiavnička Mýto p. Ďumbierom (Mýto p. Ďumbierom)	47.10	871	11.08	6.04
	Bacúch Bacúšsky potok brook (Beňuš)	28.64	809	11.19	6.70
crystalline schists, crystalline schists and smaller amount of granitoid rocks with Quaternary, mostly glacigenic and glacifluvial sediment cover	Smrečianka Žiarska dolina valley (Žiar)	17.99	781	20.05	9.41
	Račkov potok brook Račkova dolina valley (Podbanské)	35.51	932	24.48	10.74

These high values indicate the decisive influence of Quaternary glacigenic and glacifluvial sediments and of Mesozoic formations in a tectonic position upon the underground runoff. With respect to other factors the value of the average specific underground runoff was determinated to 10—22 $l.s^{-1}.km^{-2}$, and of the minimum specific underground runoff to 5—11 $l.s^{-1}.km^{-2}$. The river basin of Bystrička in Kunerád (the Malá Fatra Mts. crystalline complexes) is also ranged to this group, although the high average specific underground runoff (17.98 $l.s^{-1}.km^{-2}$) and the high minimum specific underground runoff (8.41 $l.s^{-1}.km^{-2}$) values cannot be regarded as reliable on the grounds of the existing data. The high values may, however, be due to hydrogeological function of the disturbed zone in the peripheral part of the crystalline complexes. Groundwater of the zone may be in a hydraulic interaction with limestones and dolomites of the adjacent Mesozoic formations in a complicated tectonic position.

In river basins of the West Carpathian crystalline areas, consisting of crystalline schists, mostly phyllites with thick eluvial and Quaternary deluvial covers, the average specific underground runoff was 2.99—6.86 $l.s^{-1}.km^{-2}$ and the minimum specific underground runoff ranged from 1.35 to 2.96 $l.s^{-1}.km^{-2}$.

The river basins with determined specific underground runoff consist mostly of phyllites and belong to the Volovské vrchy hills. We have not sufficient data on underground runoff from other types of crystalline schists and from other mountain ranges.

On the ground of the existing geological and hydrogeological data we cannot regard the high value of specific underground runoff in the Ida river basin because it differs markedly from the values concerning river basins consisting of analogous rocks, so the value is not considered in the determination of average specific underground runoff.

Basing on documented results (excluding the anomalous value concerning the Ida river basin) and considering the decisive factors as well as data on hydrogeologic conditions, the average specific underground runoff 2—4 $l.s^{-1}.km^{-2}$ and the minimum specific underground runoff 1—2 $l.s^{-1}.km^{-2}$ were determined for crystalline schists in the Volovské vrchy hills. We have not sufficient data on underground runoff from other crystalline schists areas of the West Carpathians, but we may presume the average specific underground runoff ranging from 1 to 6 $l.s^{-1}.km^{-2}$ and the minimum specific underground runoff 1—3 $l.s^{-1}.km^{-2}$.

In some river basins of the West Carpathian crystalline complexes are besides crystalline schists variable amounts of granitoid rocks, partly controlling the underground runoff. The average specific runoffs varied between 4.13 and 8.01 $l.s^{-1}.km^{-2}$ and the minimum specific underground runoff ranged from 2.53 to 4.60 $l.s^{-1}.km^{-2}$.

On the grounds of the results and decisive factors controlling underground runoff, and basing on the existing hydrogeological data about the West Carpathian crystalline complexes and granitoid rocks we have determined the average specific runoff 4—8 $l.s^{-1}.km^{-2}$ and the minimum specific underground runoff 2—5 $l.s^{-1}.km^{-2}$. In some crystalline areas the tectonic position of Mesozoic formations in crystalline complexes also influences the underground runoff in the areas with relatively even average specific underground runoffs ranging from 11.08 to 11.19 $l.s^{-1}.km^{-2}$ and the minimum specific underground runoff varying between 6.04 and 6.70 $l.s^{-1}.km^{-2}$.

Considering the decisive factors we may assume that the average specific underground runoff will range from 10 to 11 $l.s^{-1}.km^{-2}$ and the minimum specific underground runoff 6—7 $l.s^{-1}.km^{-2}$.

Extremely high average specific underground runoff also occurred in two river basins consisting of crystalline schists dominant over granitoid rocks with Quaternary glacigenic and glacifluvial sediments affecting the underground runoff. The extreme values of the average specific underground runoff from these river basins are 20.05—24.48 $l.s^{-1}.km^{-2}$ and of the minimum specific runoffs 9.41—10.74 $l.s.km^{-2}$. The preliminary values of the average specific underground runoff may be determined to 20—25 $l.s^{-1}.km^{-2}$ and the mini-

Table 2 Characteristic values of average and minimum underground runoff from rock environments of various types composed of West Carpathian crystalline complexes

Characteristic rock environment	Specific underground runoff ($l.s^{-1}.km^{-2}$)	
	average	minimum
granitoid rocks	2—6	0.5—3.5
granitoid rocks, crystalline schists (smaller amount)	4—6	2—3.5
granitoid rocks with Quaternary glacigenic and glacifluvial sediments and with Mesozoic carbonates in tectonic position	10—22	5—11
crystalline schists (Volovské vrchy hills)	2—4	1—2 (3)
crystalline schists (other crystalline areas)	(1—6)	(1—3)
crystalline schists, granitoid rocks (smaller amount)	4—8	2—5
crystalline schists, Mesozoic carbonates in tectonic position	10—11	6—7
crystalline schists, crystalline schists with granitoid rocks in smaller amount, with Quaternary glacigenic and glacifluvial sediments	20—25	9—11

Remark: The values in brackets are presumed on analogy and on incomplete series of hydrological measurements.

mum specific underground runoff 9—11 $l.s^{-1}.km^{-2}$. These extreme values reflect the favourable conditions for underground runoff in such areas of the West Carpathian crystalline complexes.

Table 2 shows the values of average and minimum specific underground runoffs in single rock environment of the West Carpathian crystalline complexes. The following conclusions are based on the data about underground runoff.

— The underground runoff from crystalline complexes of the West Carpathians, controlled by structural-geological and tectonical conditions, is differentiated and reflects variable permeability of the areas studies.

— The specific underground runoff values do not prove unambiguously the more favourable conditions in granitoid rocks than in crystalline schists. Some areas with crystalline schists dominant over granitoid rocks are more favourable for the underground runoff than the areas of granitoid rocks.

— The specific underground runoff values prove the decisive influence of Quaternary glacigenic and glacifluvial sediments, and of the Mesozoic formations in tectonic position on the runoff, more-or-less without respect to petrographic character of rock environment.

Regional characteristics of underground runoff from West Carpathian crystalline complexes

Regional characteristics of underground runoff from individual mountain ranges consisting of the West Carpathian crystalline complexes is based on information about decisive factors controlling the underground runoff, and on the existing hydrogeological data (Table 3).

In crystalline complexes of the Malé Karpaty Mts. the specific underground runoff was only studied in river basins consisting of granitoid rocks. In the Bystrica river basin the average specific underground runoff was low — 2.11—2.28 $l.s^{-1}.km^{-2}$ as well as the minimum specific runoff — 0.74—0.99 $l.s^{-1}.km^{-2}$. These values are characteristic of the granitoid rock environment in the area of the Bratislava granodiorite massif, and reflect the geomorphological and climatic conditions. The generally low specific underground runoffs are due to impermeable weathering cover low annual total precipitation (700—750 mm about 850 mm in top parts, higher average annual evaporation owing to higher average annual air temperature (7—9 °C) and general geomorphological position of the mountain range and a low geomorphologic dissection of the mountain range.

In the Bratislava granitoid rock massif the low average specific underground runoff ranges from 2—3 $l.s^{-1}.km^{-2}$ and the minimum specific underground runoff varies from 0.5 to 1.0 $l.s^{-1}.km^{-2}$. Basing on the present knowledge of hydrogeologic conditions we can only expect higher specific underground runoff in the Rakový potok river basin at Limbach. There the underground karst water outflows from the valley Prepadlé owing to hydrogeological function of Mesozoic formations underlying the crystalline complexes and because of differences between the geographical and hydrogeological river basins.

In the Modra granodiorite massif in the Kamenný potok river basin the average specific underground runoff is 4.46 $l.s^{-1}.km^{-2}$ and the minimum specific underground runoff is 1.70 $l.s^{-1}.km^{-2}$. Considering the decisive factors we may presume the average specific underground runoff 3—5 $l.s^{-1}.km^{-2}$ and the minimum specific underground runoff 1—2 $l.s^{-1}.km^{-2}$. In the Modra granodiorite massif are more favourable conditions for the underground runoff than in the Bratislava granodiorite massif, most likely because of more intense tectonic deformation of granodiorites and more permeable weathering zone, and consequently greater retention capacity of the rock environment.

Complicated geologic-tectonical structure in the area of Píla in the Gidra river basin represents complicated conditions for underground runoff. Besides groundwater of the Modra granodiorites the underground runoff is also controlled by groundwater of the Mesozoic formations, partly utilized for water management (the spring Vyvieračka with the yield 13—15 $l.s^{-1}$, the spring Marušina with the yield 22.5—64.0 $l.s^{-1}$).

There are no data from areas consisting of crystalline schists. Basing on the existing hydrogeological data we may in these areas presume the average values of the specific underground runoff ranging from 1 to 2 $l.s^{-1}.km^{-2}$ and of the minimum specific underground runoff varying around 0.5 $l.s^{-1}.km^{-2}$. Owing to the tectonic position of Mesozoic formations in the basement of crystalline complexes (crystalline schists) in the Hrubá dolina valley and karst springs (utilized for water management) we may expect the increased value of the specific underground runoff in the Pezinský potok river basin.

There are no concrete data about underground runoff in crystalline complexes of the Považský Inovec, Tribeč Mts., Strážovské vrchy hills, Žiar Mts. and Veľká Fatra Mts., so we evaluate the underground runoff on analogy and according to the existing data about hydrogeologic conditions.

Considering the average annual total precipitation 700—850 mm, the average air temperature (6—8 °C), evaporation values (400—500 mm) and geomorphologic conditions in the Považský Inovec Mts. crystalline complexes we presume the average value of the specific underground runoff in granitoid areas 2—3 $l.s^{-1}.km^{-2}$ and the minimum specific underground runoff 0.5—1.5 $l.s^{-1}.km^{-2}$. In crystalline areas the presumable average specific underground runoff is 1—3 $l.s^{-1}.km^{-2}$ and the minimum specific underground runoff 0.5—1.0 $l.s^{-1}.km^{-2}$. The low values of the specific underground runoff in the Považský Inovec Mts. crystalline areas are more-or-less due to thick and partly permeable eluvia and deluvia at the mountain base. Increased values of the specific underground runoff may be expected in the area of Selec owing to hydrogeological influence of the Mesozoic underlying the crystalline complexes and to differences between the geographical and hydrogeological river basins.

In the Tribeč Mts. the presumable average specific underground runoff based on decisive factors and existing data on the hydrogeologic character of the granitoid rocks environment is 2—3 $l.s^{-1}.km^{-2}$ and the minimum specific underground runoff 0.5—1.5 $l.s^{-1}.km^{-2}$ and from areas consisting of crystalline schists the values of aver. specific runoff 1—2 $l.s^{-1}.km^{-2}$ and of minimum specific underground runoff around 0.5 $l.s^{-1}.km^{-2}$.

In the Strážovské vrchy hills (Suchý and Malá Magura Mts.) the presumable average specific runoff from granitoids and crystalline schists based on the geologic-tectonical structure and on other decisive factors is 1—3 $l.s^{-1}.km^{-2}$ and the minimum specific underground runoff 0.5—1 $l.s^{-1}.km^{-2}$.

In the Žiar Mts. crystalline complexes the presumable specific underground runoff from granitoids composing the crystalline complexes there ranges from 1—3 $l.s^{-1}.km^{-2}$ and the minimum specific underground runoff 0.5—1.0 $l.s^{-1}.km^{-2}$.

In crystalline complexes of the Veľká Fatra Mts. the presumable average specific underground runoff from granitoids based on geomorphological dissection of the area the average total annual precipitation 900—1300 mm and the evaporation values is 3—5 $l.s^{-1}.km^{-2}$ and the minimum specific underground runoff 1—2 $l.s^{-1}.km^{-2}$.

As for the Malá Fatra Mts. crystalline complexes, we only have concrete data on underground runoff from the southern (Lúka) part of the mountain range.

Table 3 Regional characteristics of specific underground runoff from West Carpathian crystalline areas

Mountain range	Characteristic rock environment	Characteristic relief type[1]	Average annual total precipitation (mm)	Average annual air temperature (°C)	Preliminary evaporation values (mm)	Specific underground runoff ($l.s^{-1}.km^{-2}$)	
						average	minimum
1	2	3	4	5	6	7	8
Malé Karpaty Mts.	granodiorites (Bratislava Massif)	upland	700—850	7—9	500—600	2—3	0.5—1
	granodiorites (Modra Massif)		750—850			3—5	1—2
	crystalline schists		750—850			(1—2)	(0.5)
Považský Inovec Mts.	granodiorites	upland	750—850	7—8	400—500	(2—3)	(0.5—1.5)
	crystalline schists		700—850	6—8		(1—3)	(0.5—1)
Tribeč Mts.	granitoids	upland	650—850	7—9	500—600	(2—3)	(0.5—1.5)
	crystalline schists		700—800	7—8		(1—2)	(0.5)
Strážovské vrchy hills	granitoids and crystalline schists	upland	800—950	6—7	400—500	(1—3)	(0.5—1)
Žiar Mts.	granitoids	upland	800—950	7	400—500	(1—3)	(0.5—1)
Veľká Fatra Mts.	granitoids	highland, alpine	900—1300	3—5	450—500	(3—5)	(1—2)
Malá Fatra Mts.	granitoids	highland, alpine	900—1300	4—7	400—500	(3—6)	(2—5)
	crystalline schists, granitoids (smaller amount)	highland	900—1200	5—7	450—500	4—7	2—3.5

Explanations: [1] according to the Atlas of Slovakia (Mazúr et al. 1980) Values in brackets are presumable

Západné a Vysoké Tatry (W. and High Tatra Mts.)	granitoids	alpine, in W. Tatra partly highland	1000—1200	0—4	350—450	(5—6)	(3—4)
	granitoids, glacigenic and glacifluvial sediments, Mesozoic carbonates					19—22	7—10
	crystalline schists					(4—6)	(2—3)
	crystalline schists, glacigenic and glacifluvial sediments					20—25	9—11
Nízke Tatry (Low Tatra Mts.)	granitoids	alpine, highland	900—1500	0—4	350—500	(5—6)	(2—5)
	granitoids, glacigenic and glacifluvial sediments	alpine				10—18	5—11
	crystalline schists	highland, partly alpine		0—5		(4—6)	(1—3)
	crystalline schists, Mesozoic carbonates	highland, partly alpine				10—11	6—7
Veporské vrchy hills	granitoids	upland, partly highland	700—1100	4—7	450—550	2—6	1.5—3.5
	granitoids, crystalline schists (smaller amount)			4—6		4—6	2—3.5
	crystalline schists, smaller amount of granitoids			4—6		5—8	3—5
Stolické vrchy hills	granitoids, crystalline schists	upland, partly highland	750—1000	4—7	450—550	4—8	2—5
Volovské vrchy hills	phyllites	upland, partly highland	700—1000	4—8	450—550	2—4	1—2 (3)
Branisko Mts.	granitoids, crystalline schists	upland	650—750	4—6	500—550	(1—3)	(0.5—1.5)
Čierna hora Mts.	granitoids, crystalline schists	upland	650—700	5—8	500—550	(1—3)	(0.5—1.5)

The average specific underground runoff from granitoid rocks in the Bystrička river basin in Kunerád is 17.98 $l.s^{-1}.km^{-2}$ and the minimum specific underground runoff 8.41 $l.s^{-1}.km^{-2}$. These values are higher than in granitoid areas under analogous conditions. For example in the Slatina river basin in the Veporské vrchy hills the average specific underground runoff from granitoid rocks is 6.19 $l.s^{-1}.km^{-2}$ and the minimum specific underground runoff 3.31 $l.s^{-1}.km^{-2}$. Higher values — like in Kunerád — only occurred in morphologically dissected river basins with higher total precipitation and lower evaporation, where the underground runoff is controlled besides deformed and broken weathering zone — by Quaternary glacigenic and glacifluvial sediments and by Mesozoic formations in a complicated tectonic position in crystalline complexes or on the contact with them. The Bystrička river basin consists of granitoid rocks whose tectonic deformation is favourable for underground runoff. It is also affected by a thick cover of deluvial sediments, the distribution of fluvial sediments and afforestation. The data are overvalued even after considering the geomorphological and climatic conditions and specific underground runoff values are anomalous for granitoid rocks. The fact can so far not be interpreted unambiguously. On the other hand, the complicated geological-tectonical conditions in the peripheral parts of the Malá Fatra Mts. crystalline complexes and their contact with limestones and dolomites of the adjacent Mesozoic formations are reflected in complicated hydrogeological conditions possibly resulting in the increased values of the specific underground runoff.

The anomalous values of the specific underground runoff in the Bystrička river basin in Kunerád are not considered in the characteristics of specific underground runoffs in the Malá Fatra Mts. granitoid rocks. Basing on decisive factors of underground runoff, on the present hydrogeological information and on analogy with similar region we presume the average specific underground runoff 3—6 $l.s^{-1}.km^{-2}$ and the minimum specific underground runoff 2—5 $l.s^{-1}.km^{-2}$.

In areas of crystalline schists dominant over granitoid rocks in the Pivovarský potok river basin the average specific underground runoff is 6.64 $l.s^{-1}.km^{-2}$ and the minimum specific underground runoff 3.20 $l.s^{-1}.km^{-2}$. Basing on decisive factors and other hydrogeological data about the area of crystalline schists dominant over granitoid rocks in the Malá Fatra Mts. crystalline complexes the average specific underground runoff is presumed to range from 4 to 7 $l.s^{-1}.km^{-2}$ and the minimum specific underground runoff from 2 to 3.5 $l.s^{-1}.km^{-2}$.

As for the Western and High Tatra Mts. we have data on underground runoff mostly on southern slopes. Besides by geological-tectonical, geomorphological and climatic conditions the underground runoff is considerably influenced by glacigenic and glacifluvial sediments and by the Mesozoic formation in tectonic position. Extremely high average specific underground runoff ranging from 19.34 to 24.48 $l.s^{-1}.km^{-2}$ and the minimum specific runoff 7.11—10.74 $l.s^{-1}.km^{-2}$ are indicative of a great retention capability of these river basins.

On the basis of these results the average specific underground runoff 19—22 $l.s^{-1}.km^{-2}$ and the minimum specific underground runoff 7—10 $l.s^{-1}.km^{-2}$ were determined for the areas of granitoid rocks with glacigenic and glacifluvial sedimentary cover and Mesozoic formations in a tectonic position. The average specific underground runoff 20—25 $l.s^{-1}.km^{-2}$ and the minimum specific underground runoff 9—11 $l.s^{-1}.km^{-2}$ were determined for areas of crystalline schists or of crystalline schists prevailing over granitoid rocks with glacigenic and glacifluvial sedimentary cover.

The average specific underground runoff 5—6 $l.s^{-1}.km^{-2}$ and the minimum specific underground runoff 3—4 $l.s^{-1}.km^{-2}$ are presumed in areas of only granitoid rocks or only of crystalline schists, on the basis of incomplete series of hydrological measurements (Belanský potok—Tri Studničky) and on analogy. The average specific underground runoff 4—6 $l.s^{-1}.km^{-2}$ and the minimum specific underground runoff 2—3 $l.s^{-1}.km^{-2}$ are presumed in areas of crystalline schists.

The increased average specific underground runoff 10.60—17.52 $l.s^{-1}.km^{-2}$ and the minimum specific underground runoff 5.66—11.02 $l.s^{-1}.km^{-2}$ were found out in crystalline complexes of the Nízke Tatry (Low Tatra) Mts. in river basins composed of granitoid rocks or crystalline schists with glacigenic and glacifluvial sediments and with Mesozoic formations in a tectonic position. In other river basins an incomplete series of hydrological measurements (Klačianka, Mošnica, Demänovka) resulted in average values of the specific underground runoff 10.94—11.66 $l.s^{-1}.km^{-2}$ and in the values of the minimum specific underground runoff 5.51—8.15 $l.s^{-1}.km^{-2}$.

Considering all the results, we have determined the average specific underground runoff 10—18 $l.s^{-1}.km^{-2}$ and the minimum specific underground runoff 5—11 $l.s^{-1}.km^{-2}$ for the areas of granitoid rocks with glacigenic and glacifluvial sedimentary cover and Mesozoic formations in a tectonic position, and the average specific underground runoff 10—11 $l.s^{-1}.km^{-2}$ and the minimum specific underground runoff 6—7 $l.s^{-1}.km^{-2}$ for areas of crystalline schists with Mesozoic formations in a tectonic position. Similar and higher values may be expected in areas of crystalline schists with hydrologically significant Mesozoic formations in a tectonic position and Quaternary sedimentary cover (e. g. river basins of Vajskovský potok, Bystrá and partly Štiavnica). Higher values can also be expected in areas of crystalline schists with Quaternary sedimentary cover. The average specific underground runoff 5—6 $l.s^{-1}.km^{-2}$ and the minimum specific underground runoff 2—5 $l.s^{-1}.km^{-2}$ may on analogy and according to decisive factors be presumed for areas of granitoid rocks. Basing on analogy and on decisive factors in areas (river basins) of crystalline rocks with an insignificant Quaternary sedimentary cover we may presume the average specific underground runoff 4—6 $l.s^{-1}.km^{-2}$ and the minimum specific underground runoff 1—3 $l.s^{-1}.km^{-2}$.

In crystalline complexes of the Veporské vrchy hills the average specific underground runoff ranges from 2.79 to 7.55 $l.s^{-1}.km^{-2}$ and the minimum specific underground runoff from 1.55 to 4.60 $l.s^{-1}.km^{-2}$. In river basins in areas of granitoid rocks the specific underground runoff is 2.79—6.19 $l.s^{-1}.km^{-2}$, the minimum specific underground runoff is 1.55—3.31 $l.s^{-1}.km^{-2}$, in areas of dominant granitoid rocks the average specific underground runoff is 5.45 $l.s^{-1}.km^{-2}$, the minimum specific underground runoff is 3.07 $l.s^{-1}.km^{-2}$. In river basins in areas of crystalline schists dominant over granitoid rocks the average specific underground runoff is 6.21—7.55 $l.s^{-1}.km^{-2}$, and the minimum specific underground runoff is 3.73—4.60 $l.s^{-1}.km^{-2}$. Considering the decisive factors for underground runoff we determined the average specific underground runoff 2—6 $l.s^{-1}.km^{-2}$ for the areas of granitoid rocks, and the minimum specific underground runoff 1.5—3.5 $l.s^{-1}.km^{-2}$; the average specific underground runoff 4—6 $l.s^{-1}.km^{-2}$ and the minimum specific underground runoff 2.0—3.5 $l.s^{-1}.km^{-2}$ for the areas of granitoid rocks dominant over crystalline schists. The average specific underground runoff 5—8 $l.s^{-1}.km^{-2}$ and the minimum specific underground runoff 3—5 $l.s^{-1}.km^{-2}$ were determined for areas of crystalline schists dominant over granitoid rocks.

In crystalline complexes of the Stolické vrchy hills the average specific underground runoff ranges from 4.13 to 8.01 $l.s^{-1}.km^{-2}$, and the minimum specific underground runoff is 2.53—4.36 $l.s^{-1}.km^{-2}$. In all river basins the areal extent of granitoid rocks and of crystalline schists is variable, so considering other decisive factors we have determined the average specific underground runoff 4—8 $l.s^{-1}.km^{-2}$ and the minimum specific underground runoff 2—5 $l.s^{-1}.km^{-2}$ for both the granitoid rocks and the crystalline schists. In the crystalline complexes of the Volovské vrchy hills the average specific underground runoff ranges from 2.99—3.96 $l.s^{-1}.km^{-2}$ and the minimum specific underground runoff from 1.35 to 1.91 $l.s^{-1}.km^{-2}$. In the Ida river basin the average specific underground runoff is 6.86 $l.s^{-1}.km^{-2}$ and the minimum specific underground runoff 2.96 $l.s^{-1}.km^{-2}$. Eventual higher values in this area cannot be reasoned on the basis of the existing hydrogeological data, so we regard them as anomalous. Considering further decisive factors we have determined the average specific underground runoff 2—4 $l.s^{-1}.km^{-2}$ and the minimum specific underground runoff 1—2(3) $l.s^{-1}.km^{-2}$ for phyllites and porphyroids of the Volovské vrchy hills.

Data on long-term underground runoff in crystalline complexes of the Branisko and Čierna hora Mts. are missing. Partial data on 1—2 hydrological years runoff in several granitoid rocks and crystalline schists areas are presented by Frankovič et al. (1974, 1981). So the presumable average specific underground runoff is 1—3 $l.s^{-1}.km^{-2}$ and minimum specific underground runoff is 0.5—1.5 $l.s^{-1}.km^{-2}$ in the Branisko and the Čierna hora Mts.

Possible application of data about underground runoff on solution of basical hydrogeological problems

The data on specific underground runoff from various rock environments in crystalline complexes of the West Carpathians indicate their role in the formation of hydrogeologic conditions. The evaluation of underground runoff from various rock environment reveals its differentiation due to structural-geological and tectonical conditions, reflected in underground runoff.

In crystalline complexes composed of granitoid rocks or crystalline schists the underground runoff reflects the relation of tectonic deformation and surface weathering to total permeability. Higher values of specific underground runoff are indicative of a more favourable tectonic deformation, a greater fissure permeability and a higher permeability of the weathering zone of granitoid rock massif or of crystalline schists. For example the more favourable permeability of the Modra granodiorite massif in relation to the Bratislava granodiorite massif is indicated by the specific underground runoffs in crystalline complexes of the Malé Karpaty Mts. A detailed analysis of factors controlling permeability shows the importance of structural-geological and tectonic conditions.

The results of the specific underground runoff evaluation may be applied in the solution of the problem concerning differences in permeability of granitoid rocks and crystalline schists areas. Generally it was presumed that granitoid rocks were more water-bearing than crystalline schists. Data on specific underground runoff prove the differentiation in permeability of both types of rock environment in crystalline complexes, and in some places (Veporské vrchy hills) even a greater permeability of crystalline schists. This may result from more favourable structural-geological and tectonical conditions and from well permeable weathering zone.

The data about the average and the minimum specific underground runoff (Tables 2, 3) prove the significant hydrogeologic role of Quaternary glacigenic and glacifluvial sediments and of Mesozoic formation in a tectonic position for the hydrogeologic conditions of crystalline areas.

The concrete data also show how the anomalies in underground runoff reflect differences in structural-geological and tectonical conditions. In tectonically complicated river basin the data on underground runoff enable the determination of the influence of Quaternary sedimentary cover or of Mesozoic sediments upon hydrogeologic conditions.

Increased average and minimum specific underground runoffs are indicative of complicated geological and tectonical conditions reflected in complicated hydrogeologic conditions of crystalline complexes of the West Carpathians.

The study of underground runoff enables the solution of hydrogeological problems and indicates the necessity of the solution of some geological and tectonical problems.

The evaluation of data on underground runoff shows that as for the crystalline complexes of the West Carpathians it is necessary

— to study in detail the permeability of granitoid rocks and of crystalline schists and differences between them,
— to study the influence of Quaternary glacigenic and glacifluvial sediments upon hydrogeologic conditions,
— to study the influence of Mesozoic formations (carbonate complexes) in a complicated tectonic position upon hydrogeologic conditions in these areas,
— to pay more attention to structural-tectonical elements and their influence upon hydrogeologic conditions.

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Contamination and Protection of Fissure-karst Waters in Slovakia (Czechoslovakia)

Abstract. In mountain areas of Slovakia there still are significant, so far unexploited groundwater resources, without any particular negative interference of human activity. The groundwater resources are in fissure- and fissure-karst crystalline, Mesozoic, Paleogene complexes and in Neogene volcanics. The problem concerning protection of fissure- and fissure-karst waters is analysed on the basis of the evaluation of their regime and contamination.

Water as a part and condition of life is at present a limiting factor of the evolution of society and national economy. In fact, the water economy is one of the significant components of the state economy. The problem is in both the lack of water and its contamination evidently reducing the exploitable water resources.

In Slovakia the groundwater resources are particularly important for the present and prognostic supply of drinking water for the inhabitants, industry and agriculture in accordance with the natural conditions in the region. According to WHO the drinking water as a food component is irreplaceable as a basical source of vital elements. In this respect groundwaters are most important so their optimal utilization and protection represent the most significant task of hydrogeology.

Quaternary sediments represent the most significant resource of groundwaters for the supply of the Slovak inhabitants. A more intense utilization is obstructed by their decreasing quality due to concentrated settlement (mainly in river plains), developing industry and intensified agricultural production.

Significant groundwater resources in Slovakia are in the fissure- and fissure-karst rock environment. As regards protection, they show some specific features due to their regime and therefore a particular approach to the problem of their protection is necessary.

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Hydrogeologists and water economists concentrate their attention to fissure- and fissure-karst waters in mountain areas with still unexploited groundwater resources and lesser contamination, although also there the water quality is mediately associated with productive economical human activity.

In mountain areas of Slovakia the significant groundwater resources are mostly associated with Mesozoic limestone-dolomite complexes with fissure- and fissure-karst waters (the Malé Karpaty Mts., Nízke Tatry Mts., Inovec Mts., Strážovské vrchy Mts., the Tatra Mts., the Veľká and the Malá Fatra Mts., the Chočské vrchy Mts., the Muráň plateau, the Slovak Karst, Galmus, the Slovenský raj Mts. a. o.). Less significant are fissure waters in crystalline complexes (the Malé Karpaty Mts., Tríbeč, Vysoké Tatry, Nízke Tatry Mts., the Veporské vrchy Mts. a. o.), in Paleogene sediments (the Levočské vrchy Mts., the Spišská Magura Mts., the Oravská vrchovina upland, the Šarišská vrchovina upland, the Beskydy Mts., the Ondavská vrchovina upland, the Čergov Mts., a. o.) and in Neogene volcanics (the Štiavnické vrchy Mts., the Vihorlat Mts., the Kremnické vrchy Mts., Vtáčnik Mts., Slánske vrchy Mts., Javorie, Poľana Mts.). Mountain areas with fissure- an fissure-karst waters are for the time being only partly affected with negative human activity in contrast to the upland- and lowlands areas (including alluvial plains of the main streams). In these areas the industry and agriculture are concentrated as well as settlement agglomerations with straight negative effects upon the environment and upon the groundwater quality.

Basical problems concerning protection of fissure and fissure-karst waters

The problems of groundwater resources protection are heterogeneous. The quantitative and the qualitative aspects of the problem are closely related to each other but as regards the methodical aspects, the first one is rather concentrated upon hydrogeology and the second one upon groundwater chemistry. Reliable data can only result from a complex approach to protection including a study comprising all components of the environment and the sources of anthropogenic contamination.

For the complex approach to the groundwater protection and the rational water utilization it is necessary to know:

— basical hydrogeological and hydrogeochemical regularities of their formation in various rock environments;

— quantitative and qualitative parameters of the secondary contamination sources and the contaminants interaction mechanism in a rock environment;

— optimal mode of groundwater tapping, exploitation and distribution.

The quantitative protection is to prevent disturbances of groundwater circulation which may cause changes in their regime and negative effects upon water exploitation in respect of quantity and total destruction of groundwater resources. As regards fissure- and fissure-karst waters the negative activities may occur in both the infiltration- and the accumulation transport areas and in the discharge area. The negative influences have a different nature in single areas: The disturbance of existing circulation ways (building activities, blasting, stream regulations a. o.) their recharge with surface waters (overflow from river basin to another one, plugging of ponors a. o.) and occasionally with groundwaters from adjacent hydrogeologic structures (prevention of groundwater affluent to structures by changing groundwater regime by means of pumping from the adjacent hydrogeologic structure, a. o.).

The main purpose of qualitative groundwater protection is prevention of contaminants penetration to groundwaters or elimination of the existing contamination. There are two modes of protection:

a) preventive protection, b) consequent protection.

The preventive protection of water resources is most important and also controls functional and economical effectiveness of water economy. All aspects of environment protection must be considered and groundwater should be studied in all phases of its natural hydrogeologic cycle — infiltration, circulation, accumulation and outlet to the surface. The measures concerning preventive protection are to preserve natural conditions of formation of groundwaters and to prevent their disturbance and its negative effects upon their quality.

The consequent groundwater protection is necessary in cases of already contaminated waters owing to areal or point contamination of a latent (long-lasting) or accidental character. Then hydrogeology is to find out the areal and depth extents of contamination including the material characteristics of contaminants and to propose measures concerning prevention of increasing contamination (passive protection) and elimination of existing contamination (active protection).

The quantitative-qualitative protection comprises optimal quantitative water utilization, preserving optimal qualitative groundwater parameters. It is associated with prognosis of quantity and quality of groundwaters in respect of the formation of depression during pumping, the influence of great-yield percussive pumping upon quality, a. o. In Slovakia we have many examples of groundwater quality changes caused by interferences in the groundwater regime (e. g. intensified groundwater pumping caused extensive changes in chemical composition of waters, KULLMAN 1984; formation of large depressions during pumping and abrupt breaks in pumping caused water turbidity and a risk of lasting destruction of resources; KULLMAN 1981).

Characteristics of groundwater regime in fissure- and fissure-karst aquifers

Surficial groundwater contamination and its distribution in the rock environment is controlled by the character of permeability and circulation.

The shallow and deep groundwater circulations can be evaluated separately in respect of quantitative groundwater regime in aquifers with fissure- and fissure-pore permeability (crystalline rocks, Paleogene sediments, neovolcanics).

The shallow circulation in these aquifers exhibits many common features and is mainly associated with the zones of weathering and subsurface excavation of rocks. The groundwater runoff has the form of straight draining by surface streams. Most springs have a debris, secondary debris and fissure characters, low yields and extremely variable quantity and temperature. Deeper and hypogene circulations in single geologic formations with fissure premeability show many differences and specific features. The crystalline rock environment (granitoid rocks and crystalline schists) usually does not comprise any significant preferred zones of groundwater flow along open faults and fault zones. There are some exceptions like parts of the Veľká Fatra and Malá Fatra Mts. (around Veľká and Malá Smrekovica, Šútov) where groundwaters circulate over open faults in crystalline complexes, and areas of Mesozoic folded rocks in the Nízke Tatry Mts., forming drains and preferred ways. The existing waters on hydrogeology did not document significant differences in permeability of granitoid rocks and crystalline schists. In spite of its low transmissivity (average specific runoff 1.0—6.0 $l.s^{-1}.km^{-2}$) (Dovina 1984) and a limited deep circulation the crystalline complexes are significant for the formation of the groundwater chemical composition. The crystalline complexes form extensive, usually top parts of mountain ranges with high precipitation. They represent the initial mineralization environment of the most part of precipitation entering the weathered and subsurface-excavated zone of the crystalline complexes, and flowing over into younger geologic formations, mainly into Mesozoic carbonates, into Paleogene, Neogene and Quaternary sediments inside the mountain ranges, in foothills, in adjacent basins and lowlands (the Nízke Tatry Mts., the Tatry Mts., the Podtatranská kotlina basin). Low total dissolved solids of the waters with highly agressive effects ("hungry waters") is a factor favourable for the extension of circulation ways of groundwater, mainly in carbonate rocks of many mountain ranges into which the waters flow in and support an extensive karst development.

Paleogene sedimentary rocks with their fissure- and partly fissure-pore permeability are characterized by a more extensive deeper groundwater circulation.

According to its lithologic character and hydraulic properties (Cibuľka—Bajo 1987) the basal carbonate formation, tectonically disturbed, with its fissure- and fissure-karst permeability shows the greatest transmissivity (spring yields range from 5.0 to 30.0 $l.s^{-1}$ in many cases). Owing to tectonic and exogenic influences the fissure permeability is prevalent in formations in a sandstone- and coarse-rhythmical facies with sandstones dominant. Pore permeability is very low (spring yields range from 1.0 to 10.0 $l.s^{-1}$). Formations in a claystone-sandstone facies have a lower fissure permeability due to the claystones. Plentiful springs have small yields (0.2—0.5 $l.s^{-1}$). Formations in claystone- or microrhythmical mostly claystone facies are characterized by a very low permeability, mostly associated with the near-surface weathering zone and subsurface rock excavation (spring yields ranging zo 0.2 $l.s^{-1}$). Numerous cases of higher transmissivity (CIBUĽKA—BAJO 1987) are documented by hydraulic tests (POSPÍŠIL 1968) and by higher well yields (0.1—1.0 l . s^{-1}, sometimes 3.0 l . s^{-1}) from the Inner—Carpathian Paleogene claystones (CABALA 1976).

Besides the shallow circulation there also are a combined circulation representing drainage of loosening- and weathering zones by tectonic disturbances (spring yields 0.5—1.0 l . s^{-1}, stability coefficient 5—10), and a deep circulation associated with tectonic rock deformation extending beneath the local erosion base (spring yields above 1 l . s^{-1} and stabilitdy coefficient 3—5 and stable water temperature). Hydrogeological researches (CIBUĽKA—BAJO 1987) revealed a deeper groundwater circulation associated there with tectonic faults and fault zones favourable for accumulation and flow of groundwaters. Drilling revealed that the well yields 5—15 l . s^{-1} are frequent at the drawdown by 10—20 m. In 47 % of 36 wells (CIBUĽKA—BAJO 1987) the yield exceeded 5 l . s^{-1}. In most cases (as proved by pumping tests) the groundwater recharge to fault zones is lower than the amount of waters from wells.

Volcanic Neogene rocks in Slovakia represent a system of stratovolcanoes mostly consisting of volcanoclastic rocks and lava flows with a very complicated structural-geologic development. Alternating tectonic depresssions and elevations bounded with fault systems affect the accumulation and circulation of groundwaters. Linear fault zones in many places show favourable filtration properties and offer preferred flow-ways for groundwaters (ŠKVARKA 1974). Neovolcanic complexes have variable hydrogeologic properties and comprise rock with fissure-, fissure-pore and pore permeability. Spring yields range from 1.0 to 2.0 l . s^{-1} and average groundwater specific runoff is 2.0—5.0 l . s^{-1} . km^{-2}. Young volcanic flows and sandy tuffites are characterized by greatest permeability. Shallow groundwater circulation in neovolcanic complexes is insignificant. Dominant deep circulation in fault zones drains groundwaters from greater distances. It is proved by extensive hydrogeological operations revealing high-yield springs associated to fault zones, and high well yields. In 60 % of 20 hydrogeological wells in depths 100.0—150.0 m the documented yield per well was 10.0—150.0 l . s^{-1} which represents 600.0—700.0 l . s^{-1} of groundwaters.

In Mesozoic rocks the groundwater regime is much more complicataed, more variable and exhibits some specific features. The variable regime is mainly due to petrographically and lithologically different types of sedimentary rocks. They differ in permeability. So the Mesozoic sedimentary rocks may be divided into three groups: 1. practically impermeable rocks (claystones, marly limestones and marls, shales); 2. low-permeability rocks to high fissure-permeability rocks (sandstones, partly marly limestones, detrital limestones, dolomites, a. o.). The groundwater regime in these rocks has some common features with the regime in other geologic formations with fissure permeability (shallow groundwater circulation, limited deeper circulation on preferred ways along faults and fault zones). Mesozoic rocks with a high fissure-karst permeability (mostly Triassic limestones and dolomites, partly Jurassic and Cretaceous limestones) are characterized by a particular groundwater regime. They represent significant, tectonically complicated hydrogeologic structures with the most part of Mesozoic utilizable groundwaters. Their spatial distribution in relation to less permeable and impermeable formations, discontinuities resulting from fold deformations or apart from fold deformations (faults and fault zones) control the formation of the quantitative regime. The groundwater quantitative regime in rock environments with fissure-karst permeability differs from the regime in fissure-permeability environments as follows:

— the shallow circulation groundwater regime is either unextensive or absent;
— there are two principal zones (aeration and phreatic) with marked differences in groundwater regime;
— preferred groundwater flow ways are associated not only with open faults and fault zones but mainly with karst channels on faults and on other discontinuities;
— frequent quantitative concentrated groundwater inflow to a rock environment, in most cases connected straightly with the preferred ways of groundwater flow.

The quantitative and qualitative protection should consider the specific characters of the quantitative regime of fissure-karst waters.

Groundwater contamination and its sources

Groundwater contamination by precipitation waters

In mountain areas of the West Carpathians the groundwaters are regionally contaminated due to polluted atmosphere and precipitation waters infiltrating into groundwaters through the vegetation and soil cover. In Tab. 1a, b the average chemical composition of groundwaters in crystalline complexes of two hydrogeologically and geomorphologically different West Carpathian mountain ranges together with the precipitation chemical composition are given. The data show that in an alpine environment consisting mostly of crystalline rocks the precipitation water can bring a great portion of salts (even 50 %) into groundwaters. This is particularly significant for components indicative of anthropogenic contamination (NH_4^+, NO_3^-, SO_4^{2-}, a. o.). Chemical composition of waters from crystalline complexes at the highest level is not too different from that of precipitation waters. It is because of the minimum intensity of mineralization processes, dominant periglacial conditions and largely dissected relief supporting a rapid groundwater overflow to local erosion bases, and a low groundwater mineralization. The soils only have a slight influence upon infiltrating waters. In the lowest uplands with a more mature relief water residence is longer in the rock environment, the typomorphic influence of precipitation components (including anthropogenic mineralization) is suppressed and the chemical rock weathering as well as the metamorphic influence of the soil cover are more significant. This contamination affects variably groundwaters in prac-

Table 1a Chemical composition and some characteristics of ground waters and snow cover from different crystalline massifs

Elements	Vysoké Tatry Mts. (High Tatra Mts.)		Malé Karpaty Mts. (Little Carpathians Mts.)	
	groundwater	snowpack*	groundwater	snowpack**
T.D.S.	26.96	13.04	133.46	24.89
pH	6.1	4.70	6.80	4.48
Na	0.59	0.52	7.10	0.38
K	0.21	0.10	1.80	0.27
Mg	0.57	0.36	4,74	0.25
Ca	4.59	1.56	17.64	2.73
Cl	1.61	4.80	3.33	3.81
SO_4	5.21	2.45	37.05	7.97
HCO_3	9.16	—	30.50	—
SiO_2	2.80	0.52	16.48	0.96
NO_3	—	0.68	—	4.13
NH_4	—	0.37	—	2.07
M	31	9	81	10

Note: * Locality Lomnický štít, 2632 m a. s. l.
** Locality Bratislava-Železná studnička, 250 m a. s. l. (Data after K. VRANA et al. 1989)

tically all geologic formations evaluated. Precipitation contamination sources are out of the Slovak territory, and on the Slovak territory, mostly represented by industrial plants producing gaseous and solid exhalations, and by car traffic.

Gaseous and solid exhalations (ash and SO_2) are mostly produced on mountain range peripheries as well as in intramontane basins and contaminate the atmosphere even in the distance of 50 km. Still the mountain areas belong among the least contaminated parts of Slovakia with precipitation waters contaminated from distant sources (VRANA et al. 1989).

Contamination of precipitation is extremely variable owing to combined global and local contaminations. Table 2 shows potential total deposition of salts and SO_4, Cl, NO_3, NH_4 components from precipitation for the winter seasons of years (X-III), calculated on the basis of total precipitations and on ten years observation of snow quality (1976—1985) from selected localities in alpine, mid-mountain and lowland areas.

Table 1b Some geographical and climatic characteristics of the most different crystalline massifs

	Vysoké Tatry (High Tatra Mts.)	Malé Karpaty (Little Carpathians Mts.)
hypsography	1401—2655 m a. s. l. high mountains; periglacial processes; evident fossil glacial marks	301—700 m a. s. l. uplands
relief energy r = 2 km	640 m extremely cut relief (glacial)	101—180 m moderately cut relief to lesser extent: 181—310 m medially cut relief
climatogeographical type (mountain climate)	cold to very cold	moderately warm to moderately cold
temperature	jan. −6 to −11 °C july 4 to 13,5 °C	jan. −3,5 to −6 °C july 21 to 23 °C
snow cover	200—250 days	90—100 days
maximum of snow cover	100—150 cm	25—50 cm
annual precipitation	1400 (to 2130) mm	700—800 mm
predominant inclination	24°	6° to 14°
elementary runoff (small)	5—10	0.6—1
soil	humic-ferric podzols brown podzol soil apical parts: primitive soil (lithosols) pH 4,5 T 8 meq/100 g saturation of sorption complex: 50 % practically without $CaCO_3$ 65 % wooded (prevalent: spruce)	brown forest soil, unsaturated pH 4,5—5,5 T = 12—25 meq/100 g saturation of sorption complex: 50—75 % practically without $CaCO_3$ 80 % wooded (prevalent: oak, beech)

Note: Data from Atlas SSR

Groundwater contamination by areal and point sources from the rock environment surface

Besides global contamination of groundwaters by precipitation there also is contamination from local sources. In mountain regions they are less intensive and dispersed, only in some cases more significant surficial and groundwaters contamination occurred.

Local sources of groundwater contamination in mountain regions comprise:
— waste waters (including mine waters);
— tourism;

Table 2 Potential total deposition of salts and single components in the winter half of year (X-III) at localities selected in Slovakia (after VRANA—BODIŠ—LOPAŠOVSKÝ—RAPANT 1989)

Locality (altitude) (rock basement)	T. D. S.	SO_4	Cl	NO_3	NH_4	Character of contamination sources
	$g \cdot m^{-2}$					
Bratislava-Žel. studnička (250 m) (crystalline complexes)	8.71	2.79	1.33	1.45	0.73	Close to industrial agglomeration, mountain environment
High Tatra Mts. Lomnický štít peak (2632 m) (crystalline complexes)	5.87	1.10	2.16	0.31	0.35	Out of reach of local contamination sources
Muráň plateau (880 m) (carbonate Mesozoic formations)	6.79	2.20	0.96	1.07	0.34	Out of reach of local contamination sources
Zádielská dolina valley (570 m) (carbonate Mesozoic formations)	13.68	2.97	1.06	1.70	0.44	Alkaline wastes from magnesite mining and adjustment
Dukla (480 m) (flysch Paleogene)	8.02	2.67	1.20	1.08	0.44	Out of reach of local contamination sources
Handlová-N. Lehota (600 m). (neovolcanics)	11.58	4.06	1.77	1.68	0.43	Close to industrial area, coal mining, power engineering
Opava-Opavská hora hill (520 m) (neovolcanics)	5.97	1.93	1.15	1.14	0.32	Out of reach of local contamination sources

— car traffic;
— wood exploitation;
— agricultural production.

Significant sources of local groundwater contamination in the above mentioned environment comprise waste waters from settlements without purifying plants, and waste mine waters. Other sources are less significant, evaluated by Hanzel et al. (1984) and HANZEL—VRANA (1985).

The results of regional hydrogeochemical mapping (VRANA et al. 1984) in the area of Poľana and Javorie Mts. (in the Central-Slovak neovolcanic region) illustrate the influence of settlements upon groundwater quality. In the mountain region occupying more than 700 sqkm the lack of drinking water caused a poor settlement (10—15 inhabitants per 1 sqkm) in the past. Drinking water is still missed, although the area is attractive for tourism and recreation. The groundwater quality is mostly affected by the dispersed settlements and agriculture, resulting in a local increase of nitrates, chlorides and ammonium in wells and springs, and the developing pasturage also causes significant areal contamination of groundwater mainly along the SE margin (VRANA et al. 1984a) of the area. Forty per cent of 456 samples taken from wells, springs and hydrogeological boreholes in the years 1981—1984 were evidently contaminated secondarily. It was indicated by increased contents of nitrates (in average 34.16 $mg.l^{-1}$, about 1/3 of samples showed NO_3^- contents 40—100 $mg.l^{-1}$), chlorides (27.32 $mg.l^{-1}$ in average, with approximately 40 % frequency within 30—80 $mg.l^{-1}$), sulphates (31.31 $mg.l^{-1}$ in average, in 1/4 of samples within 46—113 $mg.l^{-1}$), and by generally increased values of Na^+, K^+ (in average 11.25 or 4.96 $mg.l^{-1}$), locally also of HPO_4^{2-} and NH_4^+. For a comparison the Table 3 gives "phon" contents of some components in petrogenic (without secondary influence) groundwaters in the area of study.

Mining waters belong among significant pollutants of the natural environment. Most dangerous are acid solutions (pH about 2—3) resulting from rapid oxidization of sulphides and containing high metals and sulphates concentrations. The acid and neutralized mine waters (owing to reaction on surroundings) have a negative influence upon quality of water in surface streams as reflected in biotopes, for example on fish population.

Table 3 Chemical composition of groundwaters in neovolcanics of Javorie and Poľana Mts.

Components	Javorie			Poľana		
	min.	max.	average	min.	max.	average
pH	5.20	8.00	6.80	5.40	7.90	6.90
T. D. S.	73.51	464.93	183.05	61.64	263.94	127.23
Na	3.00	19.10	7.45	1.70	10.60	4.58
K	0.20	25.40	2.83	0.10	11.80	2.21
Mg	1.00	18.00	5.01	0.59	15.60	3.71
Ca	8.02	68.00	23.91	1.20	31.30	13.84
Cl	0.17	81.35	8.29	0.40	15.96	3.08
SO_4	2.05	113.16	21.36	1.20	59.75	15.60
HCO_3	15.30	251.66	75.93	9.00	155.60	40.55
SiO_2	7.31	59.40	30.25	3.46	63.00	30.57
n		117			215	

Remark: n = number of samples; components except pH are given in $mg.l^{-1}$

Table 4 Comparison of trace elements content in groundwaters and mine waters from crystalline complexes of Malé Karpaty Mts. (Vrana 1981)

Rock environment of water circulation	Characteristics	Li	Sr	Mn	Fe	Zn	Cu	Ag	Cd	Pb	Cr
metapelites (phyllites, mica-schists, gneisses)	number of determinations	31	31	33	33	31	31	22	22	22	15
	frequency (%)	55	97	9	85	84	84	14	23	64	73
	dispersion of values mg/l min	0.00	0.00	0.00	0.00	0.000	0.000	0.000	0.000	0.000	0.000
	max	0.10	0.26	0.15	1.25	0.310	0.012	0.002	0.009	0.007	0.010
	arithmetic mean of non-zero values in mg/l	0.03	0.10	0.06	0.10	0.041	0.002	0.002	0.004	0.002	0.003
amphibolites	number of determin.	16	16	16	16	16	16	16	16	16	9
	frequency (%)	6	88	6	100	81	63	25	38	50	89
	dispersion of values mg/l min	0.00	0.00	0.00	0.01	0.000	0.000	0.000	0.000	0.000	0.000
	max	0.01	0.13	0.01	0.30	0.033	0.007	0.002	0.004	0.004	0.008
	arithmetic mean of non-zero values in mg/l	0.01	0.07	0.01	0.04	0.015	0.005	0.002	0.002	0.001	0.003
antimonite-mineralized layers and base metal mineralization	number of determin.	14	14	14	14	13	13	11	11	11	6
	frequency (%)	57	86	86	100	100	92	9	36	27	100
	dispersion of values mg/l min	0.00	0.00	0.00	0.02	0.009	0.000	0.000	0.000	0.000	0.003
	max	0.13	0.32	1.50	19.75	0.500	0.66	0.006	0.005	0.003	0.054
	arithmetic mean of non-zero values in mg/l	0.04	0.20	0.46	3.40	0.160	0.034	0.006	0.004	0.002	0.016

Table 5 Comparison of content of some components in groundwaters and in mine waters from crystalline complexes of Malé Karpaty (Vrana 1981)

Component	Rock environment of water circulation								
	metapelites (phyllites, micaschists, gneisses) n = 32			amphibolites n = 15			mineralized layers, antimonite and base metal mineralization (mine waters) n = 12		
$mg.l^{-1}$	min	max	$\bar{x}$	min	max	$\bar{x}$	min	max	$\bar{x}$
T. D. S.	94.4	321.8	173.6	111.1	360.5	197.4	212.4	757.7	471.3
pH	5.5	7.99	7.13	6.8	8.15	7.38	6.6	8.1	7.06
Na	2.8	12.1	6.0	2.5	10.4	4.4	5.1	12.6	7.6
Mg	2.4	15.4	7.5	4.4	14.4	6.6	5.6	45.2	22.7
Ca	10.8	45.7	24.9	14.8	79.4	34.4	41.3	134.5	83.8
SO_4	12.0	86.4	37.3	21.0	78.6	42.2	86.4	467.9	215.0
SiO_2	9.0	20.0	13.0	7.1	19.8	12.2	8.8	24.4	14.7
SO_4/T. D. S.*	—	—	0.19	—	—	0.19	—	—	0.35

Remark: * calculated from $meq.l^{-1}$; $\bar{x}$ arithmetic means; min = minimal value; max = maximal value.

Table 4 and 5 give examples of a detailed geochemical study of groundwaters in crystalline complexes of the Malé Karpaty Mts., including mine waters. The data indicate the character and intensity of mineralization processes following the technogenic interference in the natural environment, connected with mining operation on the antimonite deposit Pezinok, or negative effects of mine waters from abandoned pyrite deposits. These are high-mineralized sulphate waters with increased metal contents (Fe max. 19.75 mg . l^{-1}, Mn 20.91 mg . l^{-1}, Zn 4.97 mg . l^{-1}, Cu 0.108 mg . l^{-1}). In mine galleries more groundwaters concentrate in crystalline complexes.

Increasing mobilization of elements, mainly of toxic metals, and their transport by mine waters represent a significant contamination source for the environment in several areas of Slovakia (Vrana et al. 1984b, Rapant—Dovina 1984).

Principles of fissure- and fissure-karst waters protection

Quantitative protection is to prevent artificial interferences in the rock environment, which might cause changes in groundwater regime as well as partial or complete damage of the existing resources (excessive depletion of groundwater reserves, permanent groundwater level drawdown, decreasing yield or total loss of groundwater resources). In this respect the fissure- and fissure-karst groundwater resources are most vulnerable. It is because of a specific character of their flow, the increasing filtration anisotropy and dominant flow along preferred ways. Quantitative vulnerability of groundwaters is lower in a fissure- or fissure-karst rock environment supporting more-or-less frontal groundwater overflow in direction of their flow. The risk of quantitative vulnerability increases with filtration heterogeneity and with concentration of groundwaters in drains formed by disturbed zones, open faults, fault zones, and in fissure-karst environment also in karst channels. According to the characteristics of the groundwater regime in fissure- and fissure-karst aquifers the quantitative protection is necessary for preferred ways of deeper and deep circuits like open faults and fault zones for fissure aquifers, karst channels and surface interferences in infiltration for fissure-karst aquifers. Protective measures should be selected according to differences in groundwater circulation. Generally, in areas of open faults, fault zones and karst channels all activities jeopardizing the existing complex groundwater flow and the flow over preferred circulation ways, should be prevented. This concerns not only the phreatic (aquiferous) zone but also the aerated zone above the aquiferous one in the fissure-karst environment. Most dangerous is blasting in the area of groundwater ascent and near preferred ways. On the grounds of data on geologic and hydrogeologic conditions the places of high or low risk of destruction may be determined in the adjacent infiltration area. Hydrological investigations should precede decision about possibilities and extent of blasting in the respective areas.

The second serious factor — artificial interferences cause the lowering of the contact between impermeable basement and the overlying aquiferous complex or disturbance of the impermeable barrier followed by the lowering of the local erosion base-line of the hydrogeologic structure. The formation of a new erosion base-line may be followed by a partial or complete groundwater regime change and by disappearance of existing groundwater resources or decrease of their yield.

The third significant factor concerns fissure-karst waters. It may markedly influence the groundwater regime. It is represented by artificial interferences in the natural environment on the surface of infiltration areas of hydrogeologic structures. The interferences are charges into areas of sinkholes and ponors, increased erosion, soil wash-away due to improper deforestation, a. o. According to MIDRIAK (1980) the most intense soil erosion in Slovakia proceeded in the Belanské Tatry Mts. (degradation 9.52 mm . year^{-1}), in the Západné Tatry Mts. (8.59 mm . year^{-1}), in the Veľká a Malá Fatra Mts. (7.98—7.33 mm . year^{-1}) and in the eastern part of the Nízke Tatry (Low Tatra) Mts. Charges and increased wash of loamy and clayey material may cause sealing of underground karst channels, followed by undesirable changes in the fissure-karst groundwater regime. Liquidation of surface water ponors by sealing (with clays, loam), by tiling of surface stream channels a. o. may have the same undesirable quantitative effects.

Excessive exploitation of fissure- and fissure-karst water reserves by boreholes, wells, a. o. (ignorance of recharge conditions, erroneous groundwater reserves calculation) represents further negative interference in hydrogeologic structures. It is followed by permanent drawdown and significant changes in the regime causing a decrease of natural springs and their disappearance.

When dealing with the qualitative protection of fissure- and fissure-karst waters, we should distinguish two groups of filtration environments:

a) The filtration environment of strongly broken rocks with dense and regular fissure network (e. g. the zone of perisurficial rock deformation, strongly broken and crushed dolomites, a. o.). In its filtration character it is close to the pore environment.

b) The filtration environment of deeper and hypogene circulations with preferred ways along open faults, fault zones and karst channels.

In the filtration environment similar to the pore environment the groundwater protection is much simpler because we may apply data on protection in the pore environment in abroad and in our country. Foreign and our directions (Slovak Ministry of Health 1979) consider the aspects of groundwater protection in the pore environment also concerning the fissure environment with a similar filtration character. The direction comprise the aspect of pollution risk decreasing with the distance from the groundwater resource exploited, the criterion of 50-day groundwater stay in a rock envoronment, based on the knowledge about typhus, paratyphus and other bacteria dying in waters of the pore environment within 50 days (FREYTAG 1975).

In environment with huge open faults, fault zones and karst channels, i. e.

with preferred ways of groundwater flow are different geologic and hydrogeologic conditions for groundwater protection (E. KULLMAN 1984).

Characteristics of groundwater regime in rock environments with fissure- and fissure-karst permeability indicate the necessity of protection of groundwaters with deeper and hypogene circulations, i. e. groundwaters associated to open faults and fault zones in a fissure environment, and to the entire area of preferred ways in a fissure-karst environment. There is a problem of protection of groundwaters with deeper and deep-seated circulations in these environments when the water protection in a pore environment and in an environment of similar nature is based on invalid principles. This mostly concerns protection zones (hygienic protection zones) their delimitation and division.

It is necessary to define the entire desirable extent of the protected region (a wider protection zone, 2nd-degree hygienic protection zone), the extent and delimitation of the area demanding an increased protection (a narrower protection zone, 1st-degree hygienic protection zone) in an environment with pore groundwaters in the surroundings of the resource exploited. Frequently there are open faults, fault zones, extensive channel systems with an extremely quick transport of pollutants (e. g. oil materials, chemicals, faecal contamination, a. o.) from the contamination source to the exploitation area. This is proved by the results of evaluation of 20 groundwater-tracing tests in the fissure-karst environment of Slovakia. In most cases (75 %) the tests proved extremely high velocities of groundwater flow over preferred ways, ranging from 0.01 to 0.1 $m.s^{-1}$ (mostly from 0.02 to 0.1 $m.s^{-1}$, i. e. from 1700 to 8600 $m.day^{-1}$; KULLMAN 1984, 1986). Interesting is a comparison of these results with the prescribed 50-days residence of groundwaters in rock environment as a ciriterion for the determination of the boundary between the narrower and wider protection zones of the 2nd degree. The delay should at the velocity 0.01 $m.s^{-1}$ correspond to the passage length 43 km and at the velocity 0.1 $m.s^{-1}$ even 430 km. These data show that in Slovakia the 50-days delay in the quoted type of aquiferous environment is not applicable, because the distances surpass the dimension of hydrogeologic structures and the self-purifying ability is usually negligible in the fissure-karst environment. In accidental situation like escape of oil matter, chemicals, faecal contamination a. o. into an area with an open drain (fault, fault zone, karst channel) representing a preferred way, any protection is in most cases unreal if the preferred way is not covered with a sorption layer to slow the passage through the aeration zone into the preferred way of groundwater flow. We have not enough data about actual velocity of groundwater flow on preferred ways along open faults and fault zones in a rock environment with purely fissure aquifers (crystalline complexes, Paleogene sediments, neovolcanics) but we presume that the velocities will be essentially lower on these preferred ways mostly filled with crushed material.

It follows that increased preventive protection is much more necessary here than in environments with pore permeability. The protection should be based on the following principles (KULLMAN 1986):

1. The protected region should in fissure-karst aquifers comprise the entire hydrogeologic structure including adjacent areas supplying ground- and surface waters to the structure. A successful protection frequently depends upon a right delimitation of the structure because any part of the structure may be a place of possible damage of groundwater resources. In fissure aquifer it should be a drain formed of a fault or a fault system, and the area drained by it.

2. The division of large hydrogeologic structures into partial structures, i. e. infiltration areas adjacent to single resources or to groups of groundwater resources enable the reduction of the protected area in fissure-karst aquifers to certain parts of the structure. In most cases, under complicated geologic and hydrogeologic conditions the exact delimitation of the partial structures is practically impossible (without extremely extensive exploratory drilling and other operations). It is so difficult because it is actually the division of the structure into a hydrogeologic drainage basin with hydrogeologic divides for the phreatic zone waters, and the delimitation of the aeration zone and its parts adjacent to single hydrogeologic basins.

3. It is necessary to know the character and the extent of deformation of single parts in a structure, as well as the character of the fissure- and fissure-karst waters regime for the determination of the degree of possible groundwater vulnerability by contamination and the respective protection measures. In cases of extensive and uniform rock deformation a quick contamination of the source is hardly possible. The contamination is advancing slowly forwards extending in the most part of the structure. It may be a long process whose effects may only be observed later and be less intense.

In a hydrogeologic structure with preferred ways of flowing along open fault zones or in karst channels, the contamination in a broken rock complex with small fissures will advance slowly and be less intense due to a longer time and to the extent of effects upon the exploited groundwater resource are its interaction with the rock environment. The contamination extending straightly to the preferred ways advances quickly and is very intense.

4. The rock environment with the fissure-karst groundwater regime is physically and chemically partly inactive to most components of anthropogenic contamination. Thus the small amount of organic and mineral colloids as bearers of sorption, stabilization and elimination mechanisms increase.

Basing on these results concerning the protection of fissure- and fissure-karst waters and the delimitation of hygienic protection zones (their number, areal extent a. o.), we may draw the following conclusions:

a) A wider protective zone (2nd-degree hygienic protection zone) must be in fissure aquifers identic with preferred ways, with the entire extent of such a drain frequently extending over great distances and with the entire areal extent of adjacent rock complexes. In aquifers with a fissure-karst groundwater regime the wide protection zone must be identic with the entire hydrogeologic structure including adjacent parts of areas from which the surface and groundwaters are drained into the hydrogeologic structure. In some cases the 2nd-grade hygienic protection zone may be identic with a partial hydrogeologic structure.

b) The division of a wider protection zone (2nd-grade hygienic protection zone) of deeper and hypogene circuits into inner and outer zones is meaningless because of high velocities of groundwater flow and poor filtration abilities of fissure- and fissure-karst environments.

c) In environments with preferred ways of groundwater flow stricter protection criteria should be applied in the 2nd-grade protection zone than in pore environment.

d) The conception of the 1 st-grade hygienic protection zone should be changed and extended in contrast to pore environment where it is situated in the immediate surroundings of the groundwater resources exploited and in most cases its areal extent is small. In a rock environment with preferred ways the stricter criteria on the level of those concerning the 1st-grade hygienic protection zones should be applied besides on the immediate resources vicinity also on the rock environment parts crossed by the preferred ways. The open faults and fault zones (the preferred ways), and in fissure-karst aquifers also surface water ponors are more vulnerable by contamination than the immediate surroundings of the resources, although the contamination source may be distant (even several km) from the groundwater resources exploited.

Conclusion

The analysis of the problems concerning fissure- and fissure-karst waters protection in Slovakia shows the necessity of a thorough knowledge of the groundwater regime and circulation in single hydrogeologic structures. Otherwise we must delimitate extremely large protection zones, but the complex protection of water resources will still be questionable. Because of negative effects upon the natural environment associated with agriculture, forestry, mining, increasing tourism, water economy in mountain regions and piedmont areas of Slovakia the maximum and rational exploitation of the existing groundwater resources is necessary for supplying the inhabitants, the industry and agriculture, as well as providing their complex protection against negative interferences due to the intense social development. This has been the purpose of this paper.

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Paleohydrogeology of Mineral Waters of the Inner West Carpathians

Abstract. The paleohydrogeological outline of the West Carpathian mineral waters is based on paleogeography, hydrogeological development stages, chemical and isotopic compositions of mineral waters, their sporomorph ages, age of thermal waters and thermal regime of the territory. The mineral waters in the Alpine system of the Inner West Carpathians developed in four stages, namely Senonian-Paleocene, Eocene-Oligocene (Egerian), Eggenburgian-Karpatian and Badenian-recent.

Introduction

The recognition of the origin and genesis of mineral water chemical composition much depends on understanding the paleohydrogeology, i.e. development in space and time (O. FRANKO 1984, Y. SUN—S. XU—Z. SHEN 1986, O. FRANKO —D. BODIŠ 1987). The evaluation of this problem is based on the paleogeographic development of the West Carpathians (J. VOZÁR et al. 1978) which controls the division in individual stages of the hydrogeological development in the relevant system. As shown in Tab. 2, we consider the hydrogeological development as late as after the folding of the Inner West Carpathians, i.e. after the Laramian folding. With regard to processes that took place during the folding, we suppose that the original marinogenic waters have not been preserved in the geosynclinal sediments or if so only sporadically (the waters have been expelled from the geosyncline prior to the folding and not in the present-day spaces after the folding). Our researches are based also on the present chemical composition of mineral waters which reflects conditions under which they were formed. By the evaluation of their genesis we apply Palmer's indices modified by S. GAZDA (1974). This philosophy of the application of these indices for paleohydrogeological purposes lies in the fact that chloride-rich waters and/or S_1(Cl) constituents of Palmer—Gazda's indices are regarded as marinogenic or

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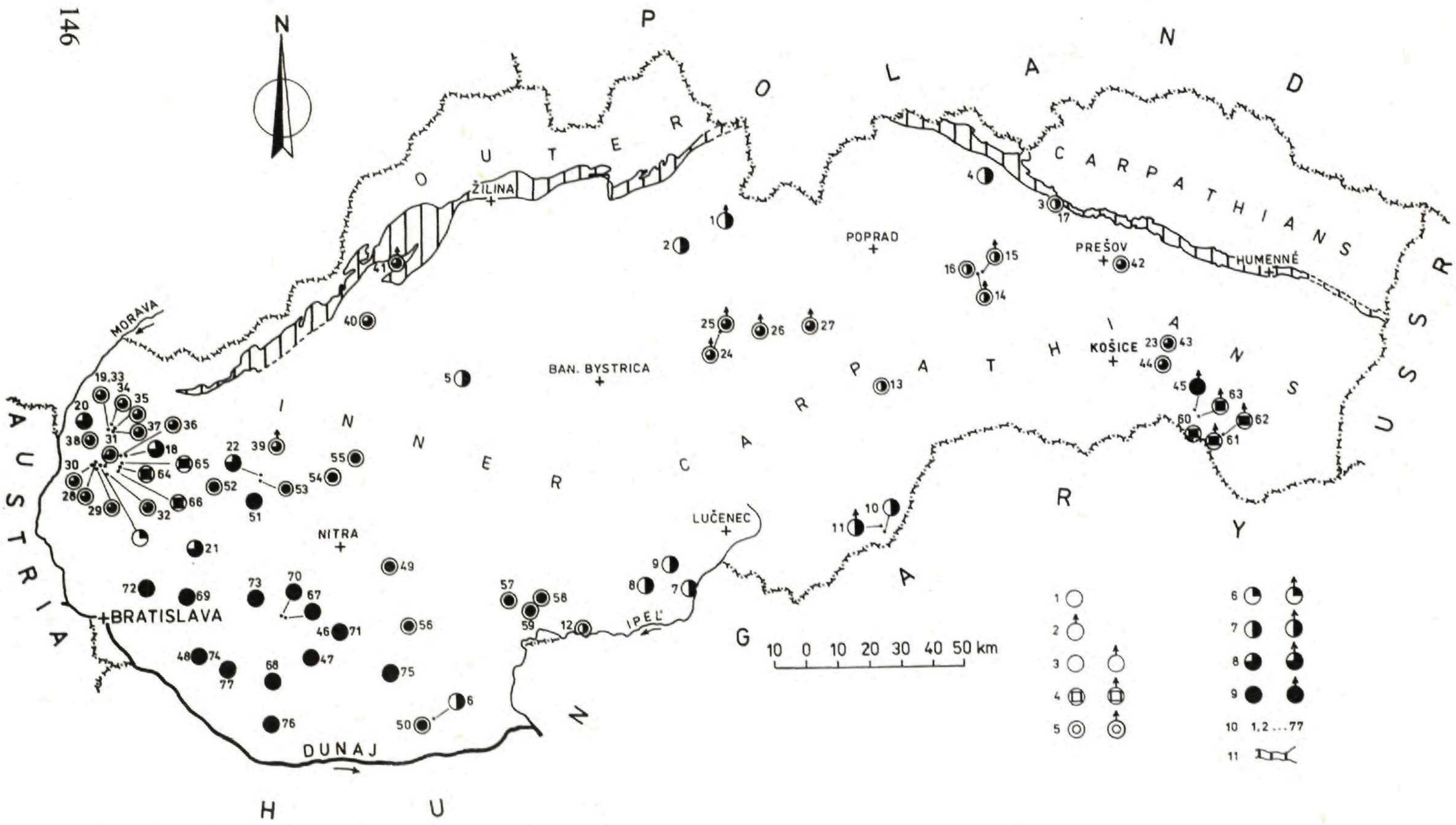

Fig. 1 Paleohydrogeology of mineral waters of the Inner West Carpathians
1 — drillholes (artificial sources), 2 — springs (natural sources), 3 — marinogenic waters, 4 — halogenic waters, 5 — seeped marinogenic mineralization, 6 — waters of the lst stage: Senonian—Paleocene, 7 — waters of the second stage: Eocene—Oligocene (Egerian), 8 — waters of the 3rd stage: Eggenburgian—Karpatian, 9 — waters of the 4th stage: Badenian—recent, 10 — 1, 2, ... 77: numbers of sources (equal to the numbers in Tables), 11 — Klippen Belt.

infiltration-degraded marinogenic (mixture of meteoric and relict sea water) and petrogenic and/or halogenic (meteoric water dissolves halite). The term "seeped marinogenic mineralization" used in the paper designates sea water of a certain age (Paleogene—Neogene) seeped or expelled, by subsidence and diagenesis processes, into seafloor sediments and under favourable hydrogeological conditions (permeable basal formations) or in the beginning of transgression even into their basement (e. g. Mesozoic Carbonates). This assumption results from the observations of chemical composition changes of porous waters of modern sea and ocean floor sediments (see e. g. O. V. Šiškina 1972, F. L. Sayles—F. T. Manheim 1975 etc.). These authors relate the chemical composition changes of porous waters of floor sediments to the rate of their deposition and associated diagenetic processes. E. g. F. L. Sayles—F. T. Manheim (1975) give an analysis of a porous water sample from a seafloor sediment depth of 684 m of Lower Miocene age where Cl (sample)/19.35 = 1.075 and virtually in all investigated samples (Deep Sea Drilling Project) varies around the value 1. In most cases, chlorides represent a conservative element. Their contents increase near the contact with evaporite formations and decrease in near-continent sediments. On the contrary Ca, Mg, Sr, K, SO_4, HCO_3, NH_4 and sometimes also Na contents depend on the surrounding conditions and sediment character. These regularities can be applied in a simplified model of mineral water paleohydrogeological development in the Inner West Carpathians. It is important to realize that, because of their complex paleohydrogeological development and water-rock interaction in a closed system and/or addition of juvenile CO_2, the original sea waters, with some exceptions, could have been preserved in the original form. Other metamorphic processes such as diffusion and membrane filtration have not so far been entirely proved in the West Carpathians. It is suggested by numerous examples from wild-cat petroleum drillholes in Tertiary basins. Although in most cases they originated about 45 m. y. ago, the development of their vertical hydrogeochemical zonality has not finished, yet. As is known, this zonality depends more or less on syngenetic salinity of the waters. In the West Carpathians, however, the situation is different — waters reflect the sedimentary environment salinity. Margins of basins where Tertiary sediment waters are influenced by the waters of marginal mountains are an exception from this rule. As an example of an unfinished vertical zonality we may mention waters from the drillhole Nová Vieska-1 in the Danube Lowland (Tab. 3, No. 6) that intersected several Tertiary epochs (Fig. 1). The sediments are predominantly of a pelitic development and the waters of the collectors tested are outside the reach of mountain margins. Another example can be mentioned from the drillhole Vlachy-1 in the Liptovská kotlina basin (Tab. 3, No. 2). In the drillhole, original marinogenic waters in a depth of 448—754 m are affected by meteoric waters. In spite of this, however, unaffected water has been preserved amidst them in a depth of 552—556 m.

Some of our suppositions can be proved by the analyses of oxygen and hydrogen stable isotopes and/or sporomorph age determinations in mineral waters as well as radio-carbon age of waters.

Table 1 Waters of wildcat petroleum drillholes Nová Vieska-1 and Vlachy-1

Drillhole	Nová Vieska-1											
Stretch from-to (m)	425.5 −465.5	1073 −1075.5	1351 −1361	1440 −1445	2029 −2030	2153 −2154	2191.5 −2192.5	2194 −2195	2351.5 −2352.5	2398 −2399	2519 −2520	2732 2736
Geol. age	Upper Panno-nian	Middle Badenian		Lower Badenian								Rupelian
T. D. S. g.l^{-1}	23.8	30.7	39.6	31.2	23.2	31.1	33.2	32.6	26.5	27.4	26.5	21.5
drillhole	Vlachy-1											
Stretch from-to (m)	200 −203	225.5 −230	448 −451	498 −501	552 −556	751 −754	1131 −1146	1161.4 −1201	—			
Geol. age	Lower Oligocene — Upper Lutetian							Neoco-mian	—			
T. D. S. g.l^{-1}	1.9	3.3	9.6	11.1	20.0	10.4	3.3	3.5	—			

Table 2 Hydrogeological development of Inner West Carpathians

Stage	Period	Period from-to (m. y.)	Duration of period (m. y.)	Folding	Region		Processes	
					dry land	sea	dry land	sea
1	Senonian-Paleocene	80—45	35	Laramide	Slovenské rudohorie ore mountains	sediments preserved in Myjavská pahorkatina upland and along Klippen Belt	denudation, precipitation water infiltration, groundwater circulation, sediment washing	deposition of sediments, soaking of marinogenic mineralization
2	Eocene-Oligocene (Egerian)	45—23	22	Savian	Slovenské rudohorie Mts; parts of Veľká Fatra Mts. and Nízke Tatry Mts.	northern area (Inner-Carpathian Paleogene) southern area (Buda Paleogene)	"	"
3	Eggen-burgian-Carpat-hian	23—16.5	6.5	Styrian	most part of region	W-E	"	"
4 (neotec-tonic)	Badenian-recent	16.5—0	16.5		mountain areas	present-system basins	"	"
					dry land — Quaternary — dry land			
					entire region		Quaternary, mineral water springs issues	

Speculations about any other origin of the chloride-rich mineral waters, e. g. juvenile (K. Malatinský 1984), are groundless for the time being. From the above it results that the present state of knowledge on the West Carpathian mineral waters allows to form a certain model of their paleohydrogeological development which will be gradually improved by new data (isotope and chemical analyses of waters and gases, hydrodynamic properties of aquifers, paleotemperature, paleosalinity etc.). In the present state of knowledge we limit ourself to the paleohydrogeology of the Inner West Carpathian mineral waters. This territory extends in Slovakia south of the Klippen Belt (Fig. 1).

Stages of hydrogeological development

In the individual stages of the Inner West Carpathian development, some parts of the territory were dry land whereas others were invaded by sea. Denudation, infiltration of meteoric waters, ground water circulation, washing of sediments etc. took place on dry land. On the territory invaded by sea and lakes, deposition and diagenesis of sediments, pressing out of synsedimentary waters from sediments during subsidence and diagenesis as well as seepage of marinogenic mineralization into rock environment took place. In both cases the processes were accompanied by water-rock interaction.

The first stage of development is represented by the period Senonian—Paleocene, 45—80 m. y. ago. Before the beginning of this period, the Inner West Carpathians were folded in the Laramian phase. This folding deformed the pre-Senonian forms and roughly what is now the Slovenské rudohorie Mts. was uplifted in the form of a megaanticline. The crystalline basement was exposed on the surface. Post-nappe Senonian marine sediments have been preserved only in the Myjavská pahorkatina hills and in isolated relics in the upper valley of the Hron river. In the Slovak karst, insignificant remnants of continental Senonian sediments occur. Marine Paleocene is known in a narrow discontinuous zone along the Klippen Belt on the northern margin of the Inner West Carpathians. Isolated remnants of marine Senonian in the upper valley of the Hron river suggest the possible presence of sea in the Paleozoic and Mesozoic of the Inner West Carpathians. Marinogenic waters have been discovered by drilling only in the Vienna Basin in the Senonian of the Myjavská pahorkatina hills. In the drillhole Závod-57 (Fig. 1), Na-Ca-Cl-type waters with T. D. S. of 16—55 $g.l^{-1}$ occur in depth of 3335—3831 m.

The second stage of development is represented by the period Eocene—Oligonene (Egerian), i. e. 23—45 m. y. ago. In this period, most of the Inner West Carpathian territory was submerged. Sedimentation took place in two areas — northern and southern, separated from each other by the above mentioned megaanticline of the Slovenské rudohorie Mts., parts of the Veľká Fatra and Nízke Tatry Mts. The northern Intracarpathian Paleogene is of marine development with transgressive conglomerates and organodetrital limestones at the base which are overlain by thick flysch sediments. The southern Buda Paleogene ranging from the Eocene to Egerian is of epicontinental development with clays, sands, limestones, marls, sandstones and in the South Slovakian Basin area with marls, conglomerates, sandy marls and sands.

The existence of marinogenic waters in the northern part of the territory is suggested by the chemical composition of waters from the spring LM-139 Žiar (Fig. 1, Tab. 3) and drillholes Vlachy-1 (claystone lithofacies), Lipany-1 (flysch lithofacies), Pu-1 Šambron (Šambron beds) and Šl-NB Koš (claystone lithofacies). At these localities, S_1(Cl) attains values of 32.3—98.4 eq% with T. D. S. 2.06—19.9 g . l^{-1} (Tab. 2). Water from the spring at Žiar and drillholes Lipany-1, Pu-1 Šambron and Šl-NB Koš is partially affected by meteoric waters (A_1 = 5.2—13.6 eq% and $rHCO_3/rCl$ = 0.17—0.26). In contrast, water from the drillhole Vlachy-1 is unaffected, i. e. it is preserved water of Paleogene age. Marinogenic mineralization seeped into underlying Triassic carbonates is indicated by waters from springs at Baldovce and Sivá Brada with S_1(Cl) 14.76 and 8.36 eq%, respectively. It is suggested also by the drillhole Klčov-l that has discovered waters of a similar chemical composition S_1(Cl) = 10.09 eq% in Triassic carbonates at depths of 135, 430 and 520 m and waters from the drillhole Lipany-l at a depth of 2955.5—3023 m, in which S_1(Cl) is 57.4 eq% (Fig. 1, Tab. 3).

The existence of marinogenic waters in the southern part of the territory is indicated by the chemical composition of waters of Oligo—Miocene sediments in the drillholes Nová Vieska-l, Bušince-l, MV-l Dolné Plachtince, SH-l/b Dolné Strháre, Cakov-2 and spring at Číž. Their S_1(Cl) attains 46.4—93.9 eq% and T. D. S. amounts to 10.26—27.6 g . l^{-1}. Marinogenic mineralization seeped into the underlying crystalline is suggested by waters from the drillholes VV-5 at Ipeľské Predmostie and KV-3 at Rochovce. Their S_1(Cl) attains 88.46 and 78.89 eq% with T. D. S. 5.45—4.18 g . l^{-1}. In the case of Rochovce it is indicated also by well-preserved Miocene sporomorphs that have been found in the drillhole water (S. Rapant—E. Planderová—D. Bodiš 1986).

After the Savian folding the stage of late-tectonic and post-tectonic molasse basin development began. It was accompanied by an intensive volcanic activity. The basins developed in two paleographically and tectonically different stages which represent the 3rd and 4th stage of hydrogeological development.

The third stage of development lasted from the Eggenburgian to Karpatian, i. e. 16.5—23 m. y. ago. This period was dominated by marine and brackish sediments independent from earlier tectonic structures. They were deposited in the originating E-W trending system of Intracarpathian basins. In the Eggenburgian the transgression advanced from the Vienna Basin through the Malé Karpaty massif into the reception basin of the Váh and upper Nitra rivers as far as the Turčianska kotlina basin. The Eggenburgian marine sediments occur also in the Modrý Kameň, Lučenec and Prešov areas. This suggests that the upper Nitra river area was connected with the Modrý Kameň and Lučenec areas in the SE and East Slovakian one in the E. During the Ottnan-

Table 3 Marinogenic mineralization of the 2nd stage of hydrogeologic development

No.	Locality	T. D. S. $g.l^{-1}$	$S_1(Cl)$	A_1	A_2	HCO_3/Cl	Cl/Br
1	2	3	4	5	6	7	8
			Marinogenic waters				
			Paleogene sediments				
1.	Žiar spring LM-139	2.06	32.23	33.65	32.16	2.08	208.0
2.	Vlachy-1 (552—556 m)	19.99	98.40	0.00	1.60	0.02	—
3.	Lipany-1 (2290—2299 m)	5.26	83.20	13.60	2.60	0.19	—
4.	Šambron drillhole Pu-l (536—546 m)	2.03	71.40	5.20	14.00	0.26	—
5.	Koš drillhole Šl-NB (803.5—806.7 m)	9.73	85.50	12.50	1.80	0.17	—
			Oligo-Miocene sediments				
6.	Nová Vieska-1 (2732—2736 m)	21.45	82,60	0.00	2.60	0.03	—
7.	Bušince-1 (624—718 m)	10.60	46.40	25.00	26.60	1.10	399,4
8.	Dol. Plachtince MV-1 (291—414 m)	27.57	72.00	5.70	22.15	0.39	242.0
9.	Dolné Strháre SM-1/b (674—750 m)	13.46	80.80	0.00	11.60	0.06	237.1
10.	Cakov-2 (240—465 m)	25.90	90.00	1.40	8.60	0.09	—
11.	Číž spring Hygiea	13.80	93.90	0.00	5.56	0.06	401.3
			seeped marinogenic mineralization				
			crystalline				
12.	Ipeľské Predmostie VV-5 (225 m)	5.45	88.46	0.00	3.57	0.05	—
13.	Rochovce KV-3 (701.5—963 m)	4.18	78.89	0.00	1.15	0.007	345.0
			Triassic carbonates				
14.	Baldovce spring Deák	4.24	14.76	0.00	69.26	4.47	1034.4
15.	Sivá Bravda spring Sv. Kríž	7.19	8.36	0.00	66.24	8.04	570.4
16.	Klčov KR-1 (520 m)	7.45	10.09	0.00	57.89	5.74	—
17.	Lipany-1 (2955.5—3023 m)	2.18	57.40	23.20	16.00	0.68	—

gian, caspibrackish sedimentation continued only in the Upper Nitra valley — Bánovská kotlina basin area and South Slovakian Basin. In the Karpatian, marine sediments deposited in the Vienna Basin, Dobrá Voda area, SE slopes of the Čachtické pohorie Mts., South Slovakian Basin and NE Slovakia. It is noteworthy that Paleogene and Mesozoic sediments of the Danube and east Slovakian Basins were eroded in this time.

The existence of marinogenous waters of this stage is suggested by the chemical composition of sediments of the above-mentioned periods (Fig. 1, Tab. 4). Na-Cl-type waters have been discovered by petroleum drillholes in the Vienna, Danube and East Slovakian Basins. E. g., Eggenburgian waters have been found in the drillhole Lakšárska Nová Ves-2 (T. D. S. = 6.2 $g.l^{-1}$), Ottnangian in the drillhole Šaštín-9 (T. D. S. = 11.9 $g.l^{-1}$), Karpatian in the drillholes Kúty-3 (T. D. S. = 9.76 $g.l^{-1}$), Cífer-1 (T. D. S. = 25.8 $g.l^{-1}$), Madunice-1 (T. D. S. = 13.3 $g.l^{-1}$) and Kecerovské Pekľany-1 (T. D. S. = 34.7 $g.l^{-1}$).

Marinogenic mineralization of this stage seeped into the crystalline is indicated by increased S_1(Cl) values in some springs of the Nízke Tatry Mts. (K. MALATINSKÝ 1984). The springs are BB-57 and 58 at Mýto pod Ďumbierom, BB-1 at Bacúch and BB-60 at Pohorelá. T. D. S. varies from 0.65 to 2.1 $g.l^{-1}$ and S_1(Cl) from 33.64 to 51.43 eq%. Isotope composition values of $\delta^{18}O$ (-9.81 to 9.86 ‰) of waters at Mýto pod Ďumbierom and Bacúch are markedly enriched in $\delta^{18}O$ in comparison with other mineral waters (-10.44 ‰ to -11.67 ‰). This enrichment suggests that the waters are meteoric with a smaller proportion of marinogenic ones. This interpretation is supported also by well-preserved Miocene sporomorphs from water of the spring BB-57 at Mýto pod Ďumbierom (S. RAPANT—E. PLANDEROVÁ—D. BODIŠ 1986).

Marinogenic mineralization seeped into Mesozoic carbonates is suggested by waters of Láb—Malacky elevation of the Vienna Basin from the drillholes Láb-90, 91, 92, 93, 106 and Malacky-22 (A. REMŠÍK—M. FENDEK—D. BODIŠ et al. 1985). High T. D. S. of waters (M = 108.2—129.7 $g.l^{-1}$), Cl/Br coefficient value (888.3—1357.3), $\delta^{18}O$ value (-2.4 ‰) from the drillhole Láb-120 and factor analysis results indicate that the waters are marinogenic ones thickened predominantly in Carpathian lagoons. Increased Cl/Br coefficient values suggest a small share of halite dissolution processes (halite disseminated in evaporites) in the formation of the chemical composition of these waters. Leaching out of halite deposits by marinogenic waters is suggested by brines of the East Slovakian Basin (Cl/Br > 10 000). E. g., in waters from the drillhole Stretava-2 the ratio is 25 763.2 and rNa/rCl ratio corresponds to stechiometric halite dissolution, i. e. the water is saturated by it (T. D. S. = 464 $g.l^{-1}$).

Waters of Závod—Studienka sunken belt from the drillholes Závod-73, 74, 77, 78 and Studienka-39 as well as those of Šaštín elevation with adjacent sunken belt from the drillholes Šaštín-9, 10, 11, RGL-2, Kovalov-6 and Borský Jur-15 are marinogenic unthickened ones seeped into Mesozoic carbonates. The waters are marinogenic, infiltration-degraded both vertically and horizontally (A. REMŠÍK—M. FENDEK—D. BODIŠ et al. 1985).

Table 4 Marinogenic mineralization of the 3rd stage of hydrogeologic development

No.	Locality	T. D. S. g.l^{-1}	S_1(Cl)	A_1	A_2	HCO_3/Cl	Cl/Br
1	2	3	4	5	6	7	8
			Marinogenic waters				
			Eggenburgian, Ottnangian, Karpatian sediments				
18.	Lakšárska N. Ves-2 (1205.5—1220 m)	6.19	83.40	12.20	3.80	0.19	—
19.	Šaštín-9 (1889—1895 m)	11.91	77.40	16.40	3.20	0.25	169.2
20.	Kúty-3 (630—633 m)	9.76	77.20	19.80	2.40	0.29	146.2
21.	Cífer-1 (1812.5—1842 m)	25.80	84.80	6.20	9.00	0.22	—
22.	Madunice-1 (1364.5—1367.5 m)	13.33	97.20	0.00	2.20	0.02	144.6
23.	Kecerovské Peklany-1 (1517—1575 m)	48.10	91.23	0.00	5.76	0.01	644.5
			Seeped marinogenic mineralization				
			crystalline				
24.	Mýto p. Ďumbierom spring BB-57	1.29	34.97	34.97	25.98	1.84	146.5
25.	Mýto p. Ďumbierom spring BB-58	2.12	35.27	35.82	23.33	1.69	160,4
26.	Bacúch spring BB-1	1.59	40.93	33.11	23.96	1.43	114.2
27.	Pohorelá spring BB-60	0.65	51.43	2.61	43.04	0.91	63.8
			Triassic carbonates				
28.	Závod-73 (4543—4532 m)	14.34	58.50	24.60	3.10	0.47	—
29.	Závod-74 (4480—4455 m)	15.61	69.30	13.30	2.20	0.22	447.1
30.	Závod-77 (4506—4460 m)	14.67	77.90	10.70	2.90	0.17	1008.3
31.	Závod-78 (4899—5000 m)	20.87	87.60	3.10	3.50	0.08	492.6
32.	Studienka-39 (1623—1628 m)	8.99	59.60	23.90	3.80	0.30	143.2
33.	Šaštín-9 (2055—2200 m)	13.08	81.20	3.40	5.00	0.10	1241.6
34.	Šaštín-10 (2275—2285 m)	5.98	65.80	17.60	2.80	0.62	372.3
35.	Šaštín-11 (2086—2116 m)	17.66	90.60	2.00	5.20	0.08	2034.5

1	2	3	4	5	6	7	8
36.	RGL-2 (2005—2570 m)	11.61	64.80	15.90	4.40	0.16	—
37.	Kovalov-6 (2249—2300 m)	8.35	49.40	0.00	7.50	0.15	325.9
38.	Borský Jur-15 (2250.5—2262.5 m)	15.58	83.20	6.00	3.20	0.11	589.8
39.	Piešťany spring Traján	1.26	17.26	0.00	23.28	1.40	1536.0
40.	Trenč. Teplice drillhole V-2	2.63	7.88	0.00	18.26	2.40	1449.5
41.	Belušské Slatiny spring Kúpelný	1.68	14.26	0.00	59.38	4.30	1068.0
42.	Prešov-1 (2923.5—2964 m)	10.90	30.40	52.00	1.80	1.78	339.8
43.	Kecerovské Pekľany (2763.5—2770 m)	12.91	89.40	6.80	2.80	0.08	534.6
44.	Ďurkov-1 (2645—2705 m)	26.81	94.40	3.80	1.80	0.06	1228.0

Marinogenic mineralization seeped into Triassic carbonates in the reception basin of the Váh river is indicated by S_1(Cl) values in thermal waters at Piešťany, Trenčianske Teplice and Belušské Slatiny. In contrast to the values around 1 eq% in similar waters at Chalmová, Kováčová and Sklené Teplice, their S_1(Cl) value varies from 7.88 to 17.96 eq%.

Marinogenic mineralization seeped into Mesozoic carbonates of the Košická kotlina basin is suggested by the waters from the drillholes Prešov-1, Kecerovské Pekľany-1 and Ďurkov-1. Their S_1(Cl) value ranges from 30.4 to 94.4 eq% and T. D. S. to 10.9—26.8 $g.l^{-1}$.

The fourth stage of development is represented by the period Badenian-recent which began 16.5 m. y. ago. A system of intramontane basins, in general equal to the present one, originated. The beginning of this neotectonic stage means the first formation of the present orographic units that was completed mainly in the Pleistocene and Quaternary. The Vienna, Danube, East Slovakian, and inner basins originated. In the Lower Badenian, marine sedimentation began in the Vienna and East Slovakian Basins and southern part of the Central Slovakian Neovolcanic mountains. Mainly brackish and continental sediments were deposited in the basins. A subsequent volcanism culminates in the Badenian and continues in the Sarmatian, Pliocene and exceptionally Quaternary. In the Upper Miocene (Pannonian) the most intensive subsidence took place in the Danube and East Slovakian Basins. The mountain areas are intensively uplifted and consequently the sinking of the intramountain depressions comes to an end. In the Quaternary, the mountain areas generally tend to be uplifted. More intensive sinking occurred in the East Slovakian, Danube and Vienna Basins. The Neogene molasse basins as well as volcanism are closely associated with the lategeosynclinal and postgeosynclinal tectonic regime of the West Carpathians. This regime resulted in segmenting the Inner West Carpathians into a number of blocks. The tectonic activity of these blocks, especially on their bundaries, stimulated the ascending of magmas characterized by the rock association rhyolite-andesite-basalt and their pyroclastics.

From the hydrogeological viewpoint, this period is the most important stage in which the present hydrogeological situation was formed. Groundwater circulation with lowering base levels of erosion gradually reaches deeper parts of rock massifs. Carbonic ground waters are associated with CO_2 formation during neovolcanic activity. CO_2 ascending and distribution of these waters are bound to deep-seated faults dividing the individual blocks of the West Carpathians. Thermal waters bound to Triassic carbonates spring predominantly along marginal faults which separate the mountain ranges from intracarpathian basins. If the Tertiary cover is thin they spring along faults also in the centre of the basins (in horsts).

Like in the foregoing stage, the existence of marinogenic waters is suggested by the chemical composition of waters from petroleum drillholes. It is noteworthy that halite was formed in the Middle Badenian of the East Slovakian Basin resulting in the formation of halogenic waters. E. g., waters from the drillhole Trhovište-26 from a depth of 1980—2125 m contain T. D. S. of 60.5—63.2 $g.l^{-1}$. The waters with this kind of mineralization include mineral waters at Byšta, Michaľany, Veľaty and Kuzmice with S_1(Cl) ranging from 56.18 to 73.78 eq%. They are primarily of halogenic origin having been secondarily metamorphosed to a different degree by CO_2. Only acidulous water at Slivník (Fig. 1, Tab. 5) is of marinogenic origin.

Waters in the Mesozoic basement in the upper part of Lakšár elevation is an exception. They are Na-Cl-type waters with T. D. S. 5—7 $g.l^{-1}$ and S_1(Cl) 58.6—85.2 eq% (Fig. 1, Tab. 6). The $\delta^{18}O$ and δD isotope compositions indicate their meteoric origin because the $\delta^{18}O$ values vary around -10.9 ‰ and δD around -77 ‰ and in a $\delta^{18}O/\delta D$ graph they lie near the line for meteoric waters and field characterizing rainfall in the vicinity of Vienna. The above facts suggest that they are meteoric waters with halogenic mineralization (Cl/Br > 10 000). This supposition is supported by a thermal anomaly in Lakšár elevation, the uper parts of which are heated by convective heat transfer by ground waters (A. Remšík—M. Fendek—D. Bodiš et al. 1985). This is also indicated by the genesis of H_2S biochemical reduction of sulphates.

In the Danube lowland there are numerous occurrences of seeped marinogenic mineralization. In the drillhole Vráble-1 in Komjatice depression, water with $S_1(Cl) = 94.8$ eq% and T. D. S. = 71.8 $g.l^{-1}$ has been found. With regard to the value of total mineralization and Cl/Br coefficient, the waters are thickened marinogenic ones of Miocene age metamorphosed in the rock-water system (indicated by a slight increase in Cl/Br ratios). On the contrary, waters of

Table 5 Marinogenic mineralization of the 4th stage of hydrogeologic development

No.	Locality	T. D. S. $g.l^{-1}$	$S_1(Cl)$	A_1	A_2	HCO_3/Cl	Cl/Br
Marinogenic waters							
Badenian, Sarmatian, Pannonian sediments							
45.	Slivník spring TV-5	5.65	25.10	60.45	13.54	2.96	496.8
46.	Tvrdošovce FGTv-1 (2037—2358 m)	20.25	90.03	0.10	6.60	0.11	—
47.	Vlčany FGV-1 (2270 m)	7.42	74.46	0.00	2.19	0.34	—
48.	Horná Potôň FGHP-1 (2000—2027 m)	11.66	76.86	22.66	0.76	0.27	—
seeped marinogenic mineralization							
Triassic carbonates							
49.	Vráble-1 (2537—2572 m)	82.20	95.20	0.00	1.80	0.03	—
50.	Modrany-1 (2085—2088 m)	23.15	76.96	0.00	5.60	0.06	—
51.	Trakovice-1 (1789—1800 m)	6.14	24.50	31.55	26.02	2.21	—
52.	Dubové-1 (2580—2596 m)	1.57	18.97	15.96	23.18	2.08	—
53.	Madunice-1 (1397—1427 m)	4.01	86.00	0.00	8.60	0.09	63.24
54.	Obdokovce-1 (2150—2500 m)	4.57	9.00	40.08	12.60	5.89	—
55.	Topoľčany FGTz-1 (1665—1676 m)	5.98	6.79	51.69	5.57	8.32	—
56.	Podhájska-1 (1155—1740 m)	19.87	86.20	0.00	8.20	0.09	—
57.	Santovka drillhole B-6	3.46	9.78	6.96	66.18	7.70	226.7
58.	Dudince drillhole S-3	5.34	12.96	17.46	52.96	5.50	202.3
59.	Semerovce SV-8 (550—570 m)	7.03	33.40	9.70	37.40	1.48	—

Table 6 Halogenic waters

No.	Locality	T. D. S. g.l^{-1}	S_1(Cl)	A_1	A_2	HCO_3/Cl	Cl/Br
60.	Byšta drillhole BŠ-1	2.87	56.18	29.18	14.02	0.77	3837.8
61.	Michaľany spring TV-3	9.94	61.53	34.14	4.18	0.62	3125.0
62.	Veľaty spring TV-7	12.08	68.20	25.06	5.92	0.46	2730.0
63.	Kuzmice spring TV-2	14.93	73.78	19.40	6.80	0.35	5945.0
64.	RGL-1 (1242—1322 m)	6.76	58.60	—	13.80	0.19	—
65.	LNV-2 (1768—1780 m)	6.03	61.40	—	13.20	0.09	1084.1
66.	LNV-4 (1999—2002 m)	6.36	61.00	—	16.00	0.26	—

Komárno marginal block (Komárno and Modrany) represent marinogenic and meteoric waters mixed in various proportions (A. REMŠÍK—O. FRANKO et al. 1979).

In Trnava embayment, waters with remains of marinogenic mineralization seeped into Mesozoic carbonates occur. This is suggested by waters from the drillholes Dubové-1, Trakovice-1 and Madunice-1, S_1(Cl) of which varies from 24,67 to 86.11 eq% and T. D. S. from 2.1 to 6.0 g.l^{-1}. In Topoľčany embayment, it is water from the drillholes Obdokovce-1 and FGTZ-1 Topoľčany whose S_1(Cl) attains 6.79 and 9.13 eq% and T. D. S. 6.5 and 5.9 g.l^{-1}, respectively (M. FENDEK—D. BODIŠ et al. 1985).

An important area of seeped marinogenic mineralization occurrence is Levice block (O. FRANKO—M. FENDEK—A. REMŠÍK 1985). Waters from the drillhole Podhájska-1 have S_1(Cl) value 86.2 eq%, T. D. S. 19.9 g.l^{-1}, rHCO_3/rCl coefficient 0.096 and that of Cl/Br 193.4. Water isotope composition ($\delta^{18}O$ -6.68 to -6.9 ‰ and δD —48.2 ‰) suggests that, in comparison with meteoric waters, these waters are enriched with oxygen and deuterium. From the above in results that the mineral waters of Levice block have a considerable share in the seeped marinogenic mineralization.

Seeped marinogenic mineralization is present in mineral waters of the Santovka—Dudince area bound to Badenian basal clastics and underlying Lower Triassic quartzites. S_1(Cl) of these waters attains 20.4 and 22.45 eq% and their T. D. S. 6.14 and 6.32 g.l^{-1}, respectively. Similar waters have been discovered in Werfenian and underlying Permian sediments in the drillhole ŠV-8 at Semerovce (Tab. 5). Waters of the central depression of the Danube lowland are interesting (O. FRANKO—A. REMŠÍK—M. FENDEK—D. BODIŠ 1984). A good scheme of their paleohydrogeology is facilitated by the knowledge of the vertical and horizontal distribution of their chemical and isotope compositions which correspond very well to each other (Fig. 1, 2, Tab. 5). T. D. S. and chloride content increase with depth, whereas hydrogencarbonate content and understandably $rHCO_3/rCl$ coefficient decrease.

This trend corresponds well with $\delta^{18}O$ content which decreases with depth from —13.18 ‰ in the drillhole Diakovce (700—800 m) to —7.31 ‰ in the drillhole DS-1 (2000—2500 m). These data prove that the sedimentary area

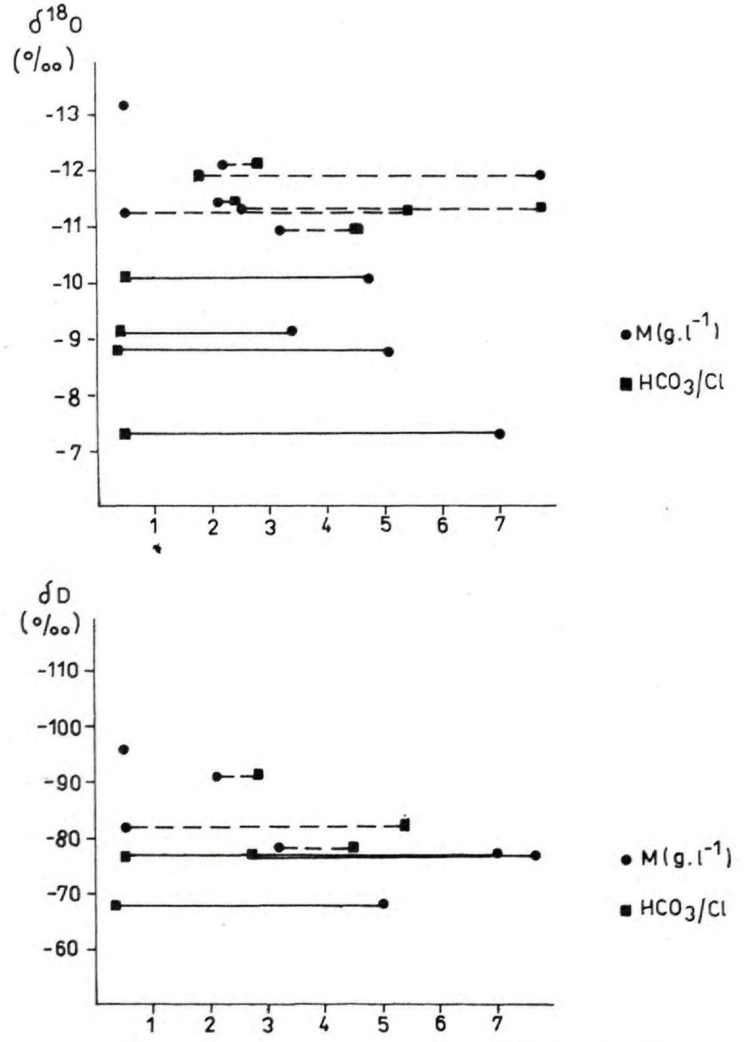

Fig. 2 Relation of the $\delta^{18}O$ and δD isotope composition to T. D. S. and HCO_3/Cl ratio in waters of the central depression of the Danube Lowland.

Table 7

No.	Locality Drillhole Depth (m)	Age of aquifers	T. D. S.	1. $\delta^{18}O$ (‰)	2. $\delta^{18}O$ (‰)	2. δD (‰)	Cl/Br	HCO_3/Cl
67.	Diakovce drillhole Di-1 710—800.0	Dacian	0.48	−13.18	−13.8	−96.0	10.29	54.95
68.	Topoľníky drillhole FGT-1 1394.4—2403.0	Pontian	2.20	−12.09	−12.8	−90.8	925.93	2.84
69.	Kráľová pri Senci drillhole FGS-1/A 910—1370.0	Pontian Pannonian	7.70	−11.93	−11.1	−77.2	–	1.72
70.	Diakovce drillhole Di-2 1416.5—1535.5	Pontian Pannonian	2.10	—11.40	—	—	—	2.35
71.	Tvrdošovce drillhole FGTv-1 1362.0—1637.0	Pontian	2.50	−11.34	—	—	—	7.70
72.	Chorvátsky Grob drillhole FGB-1/A 276.21—199.67	Pontian	0.49	−11.25	−11.5	−82.0	—	5.37
73.	Galanta drillhole FGG-1 1212.5—1470.0	Pontian	3.20	−10.97	−11.1	−78.0	493.75	4.49
74.	Horná Potôň drillhole FGHP-1 1394.0—1804.3	Pontian	4.70	−10.03	—	—	300.63	0.48
75.	Dvory n/Žitavou drillhole FGDŽ-1 1024.0—1607.0	Pontian Pannonian	3.40	−9.10	—	—	1165.38	0.43
76.	Čalovo drillhole Č-1 2284.0—2389.0	Pontian	5.06	−8.77	−9.8	−68.2	209.0	0.33
77.	Dunajská Streda drillhole DS-1 2183.0—2432.0	Pontian	7.02	−7.33	−10.9	−77.0	244.0	0.46

1. collected III. 1983
2.

*collected IV. 1976
$\delta^{18}O$ in surficial flow of the Danube River varies from −11.0 ‰ to −13.5 ‰

gradually became a fresh water one which corresponds with known geological data. It is noteworthy that the original waters are replaced by meteoric as deep as about 1500 m (on the margin) — 2000 m (in the centre), (Fig. 3). This is proved by $\delta^{18}O$ content in the Danube River water, the values of which vary between —11.0 and —13.5 ‰. We do not know, however, when they were replaced. In deeper parts the waters are mixed — marinogenic with meteoric. Data on the age of mineral waters are very important for their paleohydrogeology. The first data concerning the age of thermal waters of the Inner West Carpathians are from the upper Nitra valley (J. Šilar 1986). Radiocarbon ^{14}C measurements of thermal waters from Bojnice give an age of 8 600—12 700 years. These waters of a natural spring area collected by drillholes are 35.6—48 °C warm. The yield retardance after rainfall in the infiltration area in a spring 45 °C warm is 9 months (O. Franko 1970). It is an active water circulation in Triassic dolomites and limestones of the Choč nappe. The waters are of Ca-Mg-HCO_3 type with T. D. S. 0.7 $g \cdot l^{-1}$.

On the other hand, the age of waters from the drillhole Š-1NBII from the same rocks is 4500 years. These stagnant waters (outside active circulation) are encountered at a depth of 1677—1851 m. The circulation of the Bojnice thermal

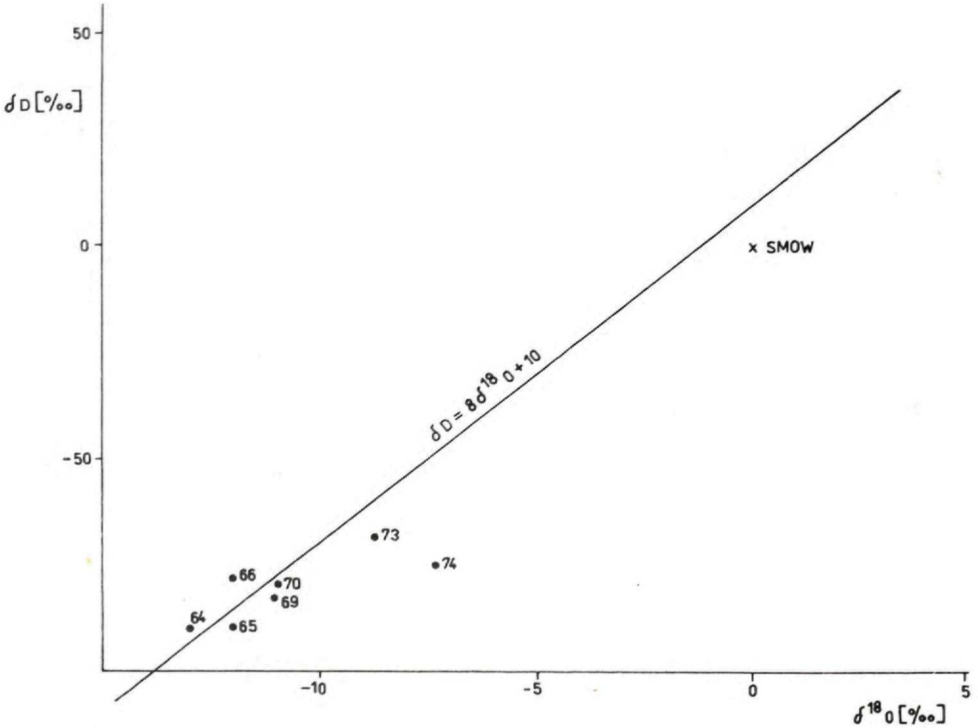

Fig. 3 $\delta D/\delta^{18}O$ ratio in some waters of the central depression of the Danube Lowland.

waters is bound to the northern part of the basin, the drillhole Š1-NBII is situated in the southern part of the basin. Water of Ca-Na-HCO_3-SO_4 type from this drillhole is 66.5 °C warm and has T. D. S. 0.84 g . l^{-1}.

On the basis of the above facts we want to mention a great difference between the retardation of pressure transfer from the infiltration area to the spring one (9 months) and retardantion of the water itself (approximately 10 000 years). On the other hand there is a great difference (about 35 000 years) between waters with active circulation and "stagnant" ones. The former date from the end of the Upper Pleistocene to Holocene, whereas the latter from the middle of the Upper Pleistocene. As the "stagnant" waters are not part of the modern hydrogeological cycle, they can be incorporated in it by drilling and subsequent exploitation. This information opens further space for prospecting and exploitation of new thermal water sources.

The most complicated stage of the paleohydrogeological development is the last one because the present state has been developing in it. Unlike the three foregoing stages, in which part of the region was dry land and some part was submerged, the situation in the Quaternary of the fourth stage is different. In the Quaternary, which has been lasting for 2 m. y., all the region is dry land (Tab. 2). Therefore the question of forming the fifth stage, that would comprise Quaternary time, arises. On the other hand the formation of this stage is in contradiction with the continuity of the territory development mainly as regards the formation of the modern orographic units and consequently also hydrogeological relations. This problem still remains unresolved.

Conclusion

Understanding paleohydrogeological development of mineral waters not only contributes to the recognition of their origin and chemical composition genesis, but it is very significant also as far as their protection is concerned. The submitted brief sketch of the paleohydrogeology illustrates that earlier views on their protection are relatively simplified. Dynamic or static reserves are commonly protected together with hydrogeological structures which they are bound to. It seems that dynamic (atmospherogenic waters) as well as static reserves of the same structure often have to be protected. In the case of static reserves the protection of marinogenic waters is accompanied by that of seeped marinogenic mineralization. Next, it is necessary to know not only the age of these waters and/or mineralization, but also the magnitude of the reserves, i. e. duration in time. On the other hand, by exploitation of such waters it is important to preserve their natural ratio. Otherwise the water quality will change in favour of one of the constituents. Another important sphere of paleohydrogeology is prospecting for new and/or so-far unknown types of mineral waters.

The submitted scheme of the paleohydrogeological development of the Inner West Carpathian mineral waters represents the first sketch. Following research has to be focused on the analysis of the individual areas (e. g. Vienna Basin). It will result in a much more complete and exact scheme of the West Carpathian development than that presented now.

Translated by Ľ. Böhmer

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Methods of research and evaluation of geothermal resources in pore environment of Pannonian Basin

Abstract. The authors inform about the methods of research and evaluation of geothermal resources in the most prosperous region of Czechoslovakia. Prognostic value of heat-energy potenial of natural resources ranges up to almost 200 MW. By the end of 1984 about 56 MW potential was proved by 19 wells. Almost all wells are used for heating buildings, glasshouses, foilhouses and swimming-pools.

Introduction

In 1984 in Slovakia the hydrogeothermal research of an extensive region in the Pannonian Basin was accomplished (FRANKO et al. 1984, 1986). It is the central depression of the Danube Basin (N promontory of the Pannonian Basin), where geothermal water is associated with Pannonian—Dacian sandy aquifer with pore permeability. The depression (Fig. 1) extending in the area between Bratislava—Galanta—Nové Zámky and Komárno, occupying about 5000 sqkm (100 × 50 km), forms a large reservoir of geothermal water. Water with surface temperature 40—90 °C is at the depth 1000—2500 m. Approximately at the same depth interval twenty geothermal boreholes were situated. On the grounds of the drilling data the region was evaluated in respect of the geothermal water exploitation.

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Research methods

Spatial distribution of geothermal water and its heat-energy potential have been investigated. This is why the geothermal boreholes were situated in calm, tectonically undisturbed areas, so that the correlation of boreholes and the interpretation of results may be as representative as possible for the entire depression.

The data resulted from the testing of about 500 m intervals from the bottom well of the boreholes up to about 1000 m beneath the land surface. On the periphery of the depressions the boreholes reached the pre-Pannonian basement, in other parts they ended at 2500 m (occasionally more) which is the capacity of the drilling rig. F-100 (formerly 2DH-75), made in Romania (technological operations were performed by the Hungarian firm VIKUV Budapest). The boreholes are situated in two, mutually perpendicular profiles, NW-SE and SW-NE striking (Fig. 1). Complementary boreholes were situated in N, E and SW parts of the region. On the grounds of positive drilling results, further exploratory — producing wells were realized (Fig. 1, Tab. 1). By the end of 1983 twenty boreholes (Tab. 1) 1500—2800 m deep, were realized, 12 of them were research holes.

The drilling was performed by the Rotary system, using clay drilling mud with 100 m and 50 m interval coring (5 m core). After every 5 m the drilling cuttings transported by drilling mud were sampled. The drilling mud was improved by bentonite, and its bulk specific gravity was 1.15—1.20 kg/dm^3. The casing diameter was 13 3/4—4 1/2". Preventer was adjusted to the casing ∅ 9 5/8; ∅ 7" is exploitation casing. This one was cemented up to the ground level in accordance with the stepping of the pump, or only up to 300 m below surface (at 300 m the casing was disconnected and the pump was stepped to ∅ 9 5/8"). The head was then stepped either to ∅ 7 "or 9 5/8".

Every casing was preceded by a complex of log measurements. The main purpose was distinction of aquifers from aquicludes, and/or determination of permeable beds and of their permeability. This was done by electrical methods (R_t, SP micro-resistivity, laterolog and continuous measurement of mud resistivity), radiological (GRL, NNL), thermometrical (measurements of bottom well temperature, continual measurements of temperature) and technical measurements (hole diameter, inclinometry). Measurements of resistivity and SP served as a basis. On the basis of the first one the degree of rock consolidation and/or porosity is determined, and the second one enables the distinction between clays and sands. Both methods depend upon drilling mud and water mineralization (the results are precised by micro-resistivity and laterolog). The shortcoming is removed by radiological log when the GR distinguished sands from clays. NNL depends upon H-content in rocks. The higher the H-content (the greater the porosity) in the rock, the smaller the anomalies on the curve, and vice versa.

Hydrodynamical tests determined mainly hydraulic parameters of aquifers,

Table 1. Geothermal bore-holes realized in 1971—1983

Locality	Well	Open segment from to (m)	Outflow yield Q ($l.s^{-1}$)	Water temperature T (°C)	Heat power P_t (MW)	T. D. S. (g/l)	Chemical composition of water (ions > 10 eq%)	Chemical composition of gases (gases dispersed in water, > 10 vol%)
Exploratory wells								
Kráľová pri Senci	FGS-1/A	1 370—910	13.0	52.0	2.01	7.7	HCO_3-Cl-Na	CO_2-CH_4-N_2
Topoľníky	FGT-1	2 487.5—1 394	23.0	74.0	5.68	2.2	HCO_3-Cl-Na	CH_4-N_2
Komárno	FGK-1	1 082—904	4.0	45.0	0.50	2.0	HCO_3-(Cl)-Na	CH_4-N_2-CO_2
Galanta	FGG-1	1 470—1 212.5	10.8	62.0	2.13	3.2	HCO_3-Cl-Na	CO_2-N_2-CH_4
Tvrdošovce	FGTv-1	1 637—1 362	20.0	70.0	4.60	2.5	HCO_3-Na	CO_2-CH_4-N_2
Horná Potôň	FGHP-1	1 804.3—1 394	20.0	68.0	4.43	4.7	Cl-HCO_3-Na	CH_4-N_2-CO_2
Čilistov	FGČ-1	1 549—1 195	15.0	52.0	2.32	6.9	HCO_3-Cl-NA	CH_4-CO_2-N_2
Dvory nad Žitavou	FGDŽ-1	1 607—1 024	7.2	62.0	1.42	3.4	HCO_3-Cl-Na	CH_4-CO_2-N_2
Vlčany	FGV-1	1 852—1 244	10.0	68.0	2.22	2.1	HCO_3-Na	CO_2-CH_4-N_2
Gabčíkovo	FGGa-1	1 926—1 122	10.3	53.0	1.64	1.1	HCO_3-Na	CO_2-N_2-CH_4
Galanta	FGG-2	2 032—1 706	25.0	80.0	6.80	4.9	HCO_3-Cl-Na	CO_2-N_2-CH_4
Boheľov	GPB-1	—	observation well			—	—	—
Exploratory-exploitation wells								
Dunajská Streda	DS-1	2 432—2 183	15.2	91.5	4.87	6.9	Cl-HCO_3-Na	CH_4-CO_2-N_2
Čalovo	Č-1	1 790.5—1 573	10.0	78.0	2.59	1.1	HCO_3-Na	CH_4-CO_2-N_2
Senec	BS-1	1 181.4—928.4	12.0	49.0	1.70	2.5	HCO_3-Cl-Na	CO_2-N_2-CH_4
Diakovce	DI-1	1 535.5—1 416.5	12.0	68.0	2.66	2.1	HCO_3-Cl-Na	CH_4-N_2-CO_2
Nové Zámky	GNZ-1	1 473—1 236	4.5	59.0	0.83	3.2	HCO_3-Cl-Na	CO_2-CH_4-N_2
Čalovo	Č-2	1 438.9—1 073.16	18.2	57.0	3.2	0.9	HCO_3-Na	—
Šaľa	HTŠ-2	1 169—860	3.13	42.3	0.36	1.5	HCO_3-Na	N_2
Galanta	FGG-3	1 998.5—1 731.0	25.0	77.0	6.49	5.9	HCO_3-Cl-Na	CO_2-N_2-CH_4
Total	—	—	273.53	42.3—91.5	56.44	—	—	—

peripheral conditions of hydrogeologic structures, the yield of sources, pressure, temperature, T. D. S. and chemical composition of water. The modes of opening the aquiferous beds and of their testing were selected according to the hole depth. For example in the case of drilling to 1500 m (Kráľová pri Senci), the beds to 1200—1500 m deep — because of their diagenetic uncementing and possible inflow of sand into well, were made up of a netting-wrapped filter. The segment above the filter was cemented through a window. The screen pipe was prepared on the surface, the holes were utilized, perforation ranged to 20 %. In case of drilling to 2500 m the beds deeper than 1200—1500 m were open by "jet" perforation of cemented casing (24 blows/m). The deepest segment was also cased by perforated 4 1/2" pipes. Testing of the beds proceeded from the bottom to the top and most frequently the sequences were tested in 500 m intervals. To get the highest possible yield, all permeable beds thicker than 4 m were open in the intervals. On single open segments hydrodynamical tests were performed by the organization performing the drilling. The tests consisted of 2 parts:

— starting the drill hole operation,
— short-term hydrodynamical test.

The drill hole operation started with replacing the drilling mud by technical water, followed by pumping of water from the hole to its purification by compression. Hydrometric propeller was applied in case of unreliable filter functioning. The quality of water up to its purification from the drilling mud was monitored by measuring the temperature and conductivity.

Purification of water from the drilling mud was followed by short-term hydrodynamical tests consisting of:

— measuring the drilling depth, the bottom well temperature, the open-beds temperature,
— recovery test (Fig. 2) for 48 hrs,
— measurements of yield at 4 depressions. The first depression lasted as long (6 hrs) as the linear course in the length of one logarithmic cycle appea d in semilogarithmic scale (yield vs log time). Following depressions lasted as long as the first one. The last one lasted at least twice so long as all depressions. The yield and water temperature were measured on the surface. At each depression also the water pressure on the surface and in the centre of open segment was measured. By separator the gas volume was determined and water and gas were sampled for physical-chemical analyses;
— measurements of water pressure gradient in the well on every 100 m (condensated when necessary) to determine the gas bubble point,
— determination of temperature distribution by continuous water temperature measurement in the well, on every 300 m the temperature was measured by controlling maximum thermometers. The pressure and temperature gradients were measured at equal well yields;
— measurements of affluent distribution by hydrometric propeller;
— recovery test for 3 × 48 hrs. The pressure was measured on the surface and in the centre of the open segment (Fig. 2).

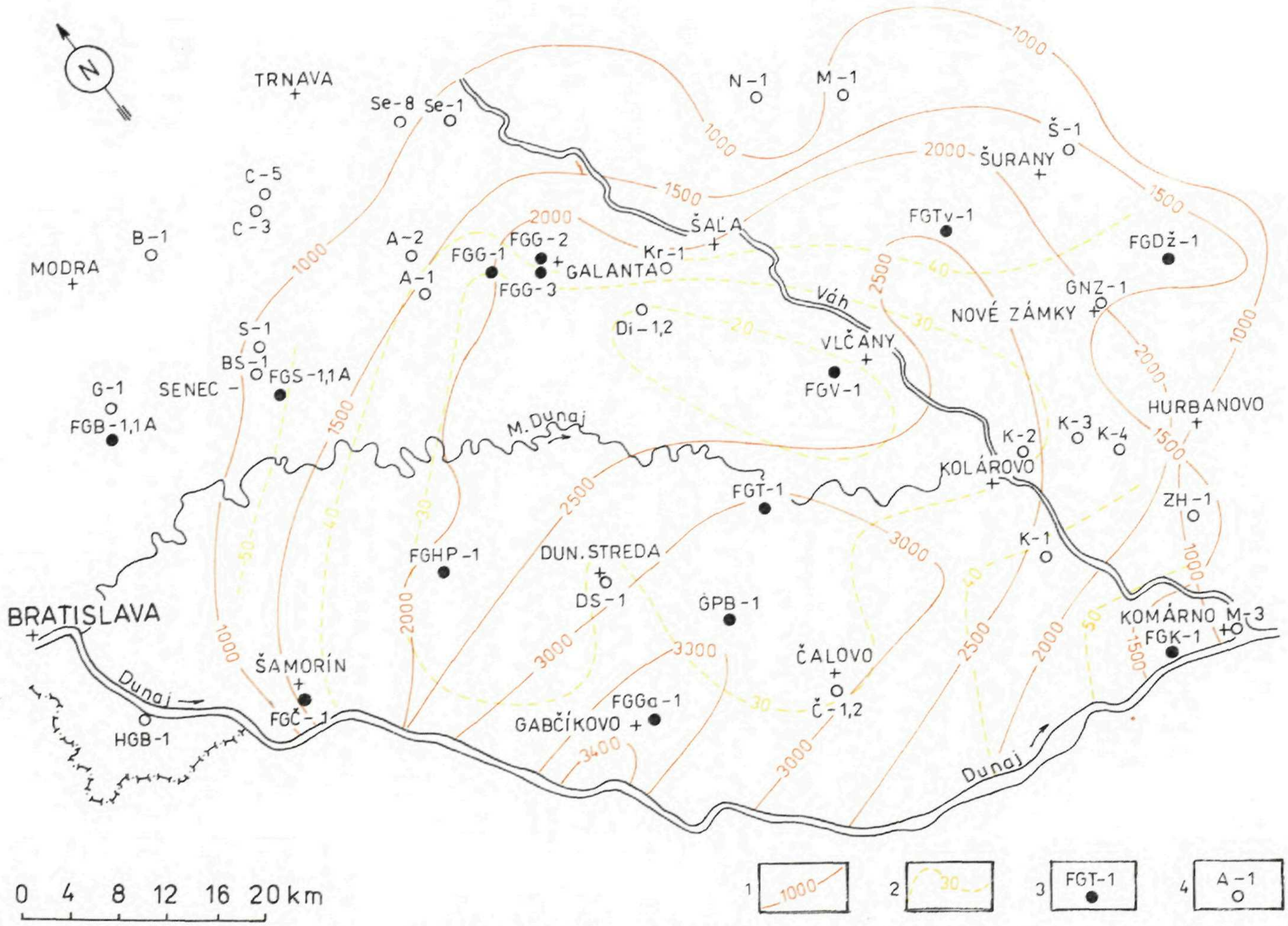

Fig. 1 Spatial delimitation of geothermal water reservoir in central depression of Danube Basin
1 – Pannonian base isolines, 2 – percentage of aquifers, 3 – geothermal well, 4 – oil well

GÚDŠ EČ 7-1989

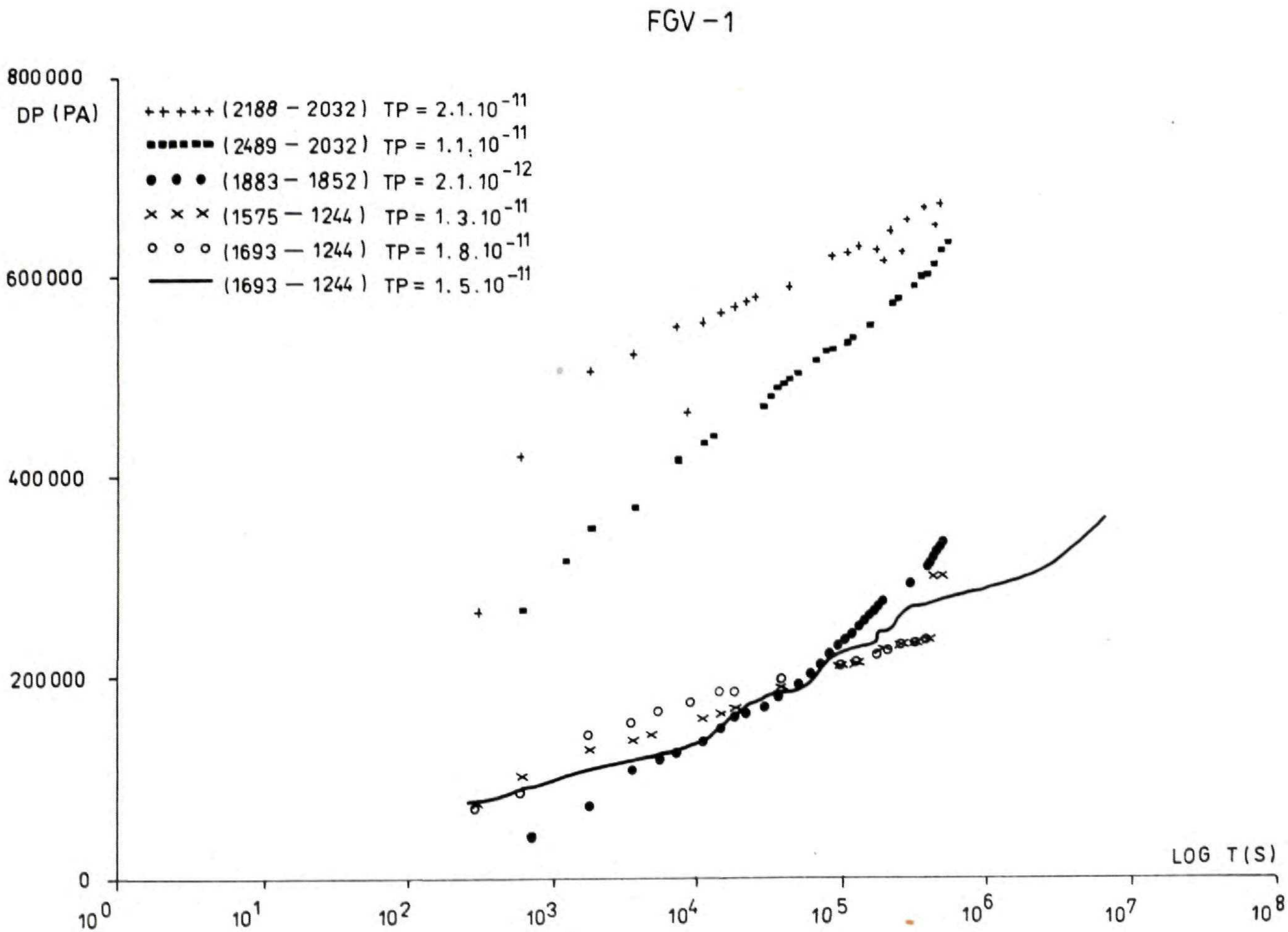

Fig. 2 Recovery tests on single intervals in well FGV-1 Vlčany

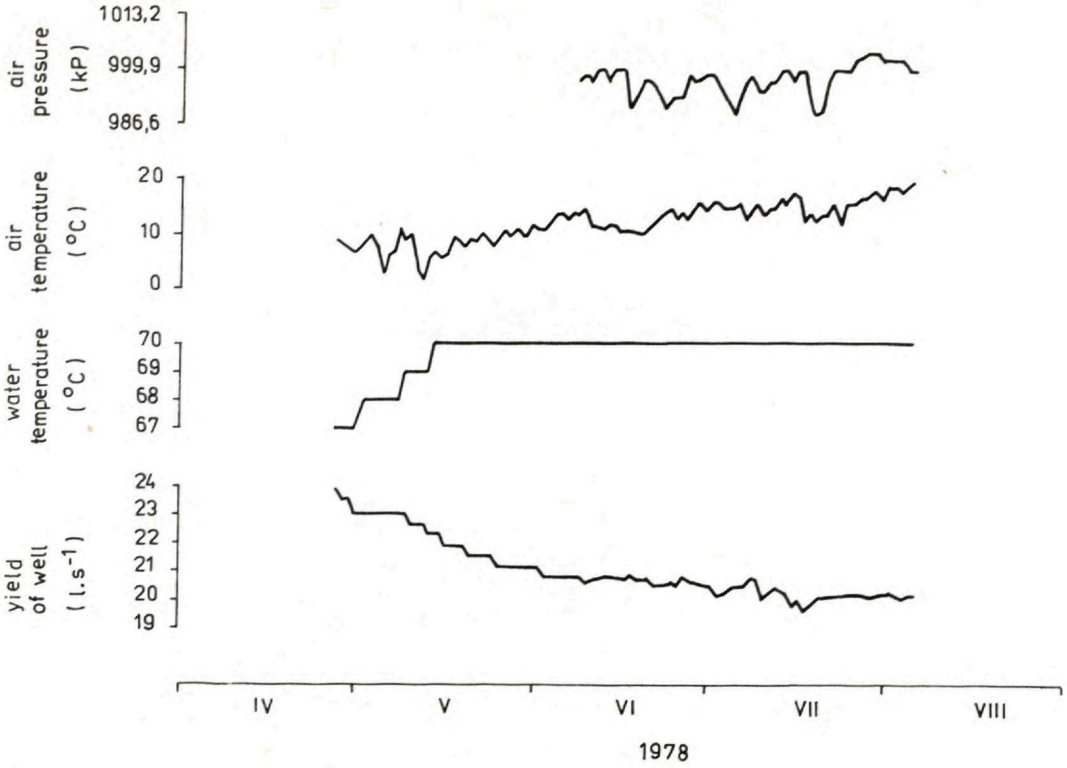

Fig. 3 Regime measurement of water from well FGTv-1 Tvrdošovce

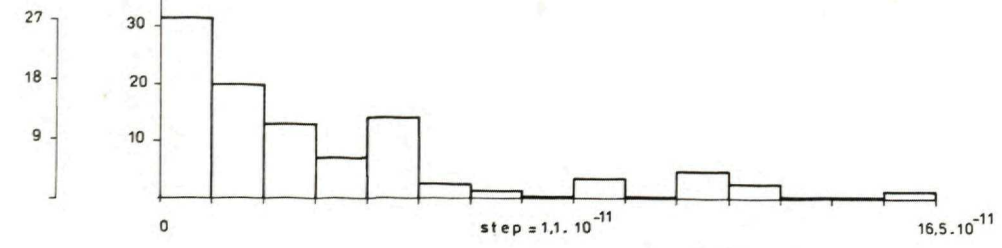

Fig. 4 Histogram of distribution of absolute transmissivity coefficient (T_p) values

A long-term hydrodynamical test was performed in the segment to be exploited. The test consisted of 3 months' observation of free outflow (Fig. 3) and a consequent long-term recovery test (Fig. 2).

Evaluation methods

The structure of the reservoir

The reservoir is filled with Quaternary, Rumanian, Dacian, Pontian and Pannonian sediments. The Quaternary and Rumanian sediments are represented by gravels and sands, other stages by alternating clays and sandy clays with sands and sandstones. The depression originated in the Pannonian and developed up to the end of the Pliocene. It was a subsidence by bending, partly compensated by subsidence along faults. The depression has a dish-like brachysynclinal structure without respect to the pre-Pannonian basement (PRIECHODSKÁ—VASS 1986).

To illustrate the dish structure of the depression we have compiled stratigraphical sections and stratigraphical level maps.The levels in depth 1000, 1500, 2000, 2500 and 3000 m below surface level have been chosen. Hydrogeological complexes were included in the sections and maps and stratigraphical-hydrogeological maps and sections were the result. They show the structure of the depression and the distribution of hydrogeological complexes in single stratigraphical levels, as well as stratigraphical range of the intervals tested in wells.

Hydrogeothermal characteristics of the structure studied is based on spatial delimitation of the geothermal water reservoir, the division of the reservoir into hydrogeological complexes, hydraulic parameters of the complexes, pressure conditions of geothermal waters, geothermic conditions, hydrogeochemical and technological characteristics of geothermal waters. Complementary characteristics are given in the following chapters. Hydrogeothermal conditions were evaluated as follows. Because of alternation and wedging-out of clays and sands in the reservoir and (mainly) vertical zonation of aquifer permeability and chemical composition of waters irrespective of stratigraphical levels we could not have kept to the stratigprahic sections and maps. We had to compile sections of hydrogeologic complexes at first and then level maps of the complexes. Then the hydraulic parameters, temperature parameters, chemical composition and mineralization of waters were included in the sections and maps. This procedure resulted in hydrogeothermal sections, level maps, and hydrogeochemical sections and level maps. They are significant for further exploratory-exploitation wells.

Spatial delimitation of reservoir

The geothermal water reservoir is spatially delimitated by two boundary conditions (Fig. 1). The first is the 40 °C water temperature. Waters of this and a higher temperature may be utilized for direct heating. So the hydrodynamical tests on wells have only been performed to the approximate depth of 1000 m. At this depth the reservoir temperature is about 45—50 °C and the surface temperature about 40 °C. The yield of outflow from wells with temperatures below 40 °C is low due to the low effect of thermolift (FRANKO—FENDEK 1985). The reservoir top is confined with a plain at 1000 m depth. The second boundary conditions is the course of the impermeable basement (aquiclude) of the reservoir. A complex of aquicludes or a hydrogeological complex 5 (see below) irrespective of its stratigraphical range is regarded as the impermeable basement. The absolute transmissivity coefficient T_p in this complex is smaller than $0.5 \,.\, 10^{-11}$ m^3 (see below), so the area of the reservoir at the depth 1000 m is given by the intersection of the plain with the impermeable basement — the aquiclude. Since the structure of the depression is dish-like, the impermeable basement slopes down to the depression centre from all sides. From the margins the basement is dipping at 30° and the dipping is decreasing towards the centre. The maximum depth of the reservoir is 3300—3400 m in the area of Gabčikovo — i. e. in its centre. The maximum length of the reservoir at the level of 1000 m is 60 km in the NE-SW direction and almost 70 km in the NW-SE direction.

Characteristics of hydrogeological complexes

Hydrogeological complexes represent various bed complexes with variable typical hydrological characters and properties controlled by lithologic composition of beds in single complexes. The hydrogeological complexes comprise variable portions of sand beds, sandstone or gravel beds representing thermal water aquifers, and clay representing aquicludes. Sandy clays and clayey sands, mostly fine-grained, represent aquitards.

Single hydrogeological complexes were in vertical sense distinguished according to lithologic composition of beds and log diagrams of wells. Decisive was the percentage of aquifers and aquicludes, their thickness, alternation of resistance and potential properties of sediments. In horizontal plain the hydrogeological complexes either link up to one another or are interlocked. The borders of hydrogeological complexes in the horizontal level are presumable in wider areas of wells. The spatial delimitation of hydrogeologic complexes is schematical. The idea of their spatial position is presented in level maps (Fig. 5) and sections (Fig. 6, 7).

In the depth interval 0—3000 m in Badenian—Quaternary sediments six hydrogeological complexes have been distinguished. The data on the complexes were treated statistically and graphically by the personal computer WANG 2200 B. All complexes are presented in Table 2. The occurrence of the delimitated hydrogeological complexes below 3000 m is presumable. Thickness of single hydrogeological complexes ranges from 5 to 1174 m. Their succession is relatively regular in places and correlable with a wider surroundings. In some places their vertical and horizontal successions are irregular and reflect the complicated Neogene sedimentation in the depression.

One hydrogeological complex may occur repeatedly in the vertical well log. Only the complexes 1 and 2 have a stable succession. The complex 1 always has the position of an overlier. The hydrogeological complex 5 preserves a stable position. It is also in the filling of the depression, forms a continuous impermeable basement of single hydrogeological complexes and actually of the entire hydrogeothermal structure.

The hydrogeological complex 1 represents a complex of aquifers — beds of gravels and sands (Rumanian—Quaternary). In some places are thin discontinuous clay beds. The thickness of the complex ranges from 5 to 462 m, in 60 % of cases it ranges from 5 to 75 m. The complex 1 is in the depth interval 0—462 m and always overlies the complex 2. Its contact with other complexes is conspicuous.

The hydrogeological complex 2 represents a complex of alternating aquifers and aquicludes in an approximate equilibrium (tolerance ± 13 %). The complex 2 always underlies the complex 1 and occurs also in deeper segments. Its borders in relation to hydrogeological complexes 1, 3, 5 are conspicuous, and in relation to complexes 4 and 6 — less conspicuous. The complex ranges from 55 to 1174 m in thickness and occurs in the depth interval 5—2800 m. The per cent of aquifers is 27.7—67.6 %, of aquicludes 23.7—66.3 and of aquitards 5.0—39.3. In the upper and lower parts of the complex are thick continuous bodies of Pannonian—Rumanian rocks.

The hydrogeological complex 3 is characterized by aquicludes dominant over aquifers with thick clay beds alternating with thin sand beds. Its contact with the complexes 2 and 6 is conspicuous, the contact with the complexes 4 and 5 is less distinct. Its position in relation to the complexes is variable. The thickness of the hydrogeological complex 3 is 309—924 m. The complex is in the depth interval 124—2130 m. The percentage of aquicludes is 24.6—87.5 %, of aquifers 12.5—26.9 %, and of aquitards 15.2—52.1 %. The complex 3 forms large continuous bodies of Pontian—Dacian rocks in the centre of the depression.

The hydrogeological complex 4 is characterized by aquicludes dominant over aquifers with clay beds alternating with thinner sand or sandstone beds. Its borders in relation to hydrogeological complexes 2 and 3, partly 5 are less conspicuous, but its contact with the complex 6 is distinct. The thickness of the complex is 132—1121 m. The complex is in the depth interval 129—2450 m. The percentage of aquicludes is 14.3—81.0 %, of aquifers 5.1—41.4 %, and aquitards 11.0—80.6 %. The complex 4 forms huge continuous bodies of Sarmatian—Rumanian rocks in various parts of the depression filling. The complex is resembling the complex 3, only it displays dominance of alternating aquicludes and aquifers and the number of aquicludes thicker than 48 m decreases whereas in the complex 3 it increases.

The hydrogeological complex 5 is a complex of aquicludes with absolutely dominant thick clay beds with occasional thin sandstone or sand beds (Badenian—Rumanian). Its contact with the complexes 2, 4 and 6 is con-

Table 2. Presence of aquifers, aquitards and aquicludes in hydrogeological complexes of the basin

Hydrog. complex	Occurrence in interval from to (m)	Thickness (m)	Age	Aquifers			
				Number	Thickness	Σ(m)	%
1	0—462	5—462	Quaternary-Rumanian	1—17	3—230	3—340	73.2—100.0
2	5—2800	55—1174	Rumanian-Pannonian	2—50	3—54	26—487	27.6—67.6
3	124—2130	309—924	Dacian-Pontian	4—19	3—33	60—128	12.5—26.9
4	129—2450	132—1121	Rumanian-Sarmatian	3—41	3—33	22—333	5.1—41.4
5	100—3000	95—950	Rumanian-Badenian	1—24	3—32	10—226	4.2—28.3
6	276—1877	187—567	Pontian-Sarmatian	7—23	4—55	101—317	50.9—55.9

spicuous, with the complex 3 it is less distinct. The complex 5 besides occurring in the depression filling also forms continuous impermeable basement for single hydrogeological comlexes and so for the entire geothermal water reservoir. The thickness of the complex is 95—950 m. It is in the depth interval 100—3000 m. The percentage of the clay beds is 62.2—100.0 % and of sand or sandstone beds 4.2—28.3 %, aquitards are absent.

The hydrogeological complex 6 is characterized by aquifers dominant over aquicludes. Thick and thin sandstone or sand beds alternate with thin beds of clay and marls (Sarmatian—Pontian). The contact of the complex 6 with the complexes 3, 4, 5 is distinct, with the complex 2 less distinct. The complex 6 only occurs in the western part of the depression and around Tvrdošovce. The thickness of the complex is 187—567 m. It is in the depth interval 276—1877 m. The percentage of aquifers is 50.9—55.9 %, of aquicludes 25.7—44.1 %, and of aquitards 20.3—22.3 %.

Hydraulic parameters

The hydraulic parameters as basical characteristics reflect hydrophysical properties of rocks. Aquifers are represented by sands and sandstones aquicludes by clays, sandy clays and marlstones. The aquifers were tested by short-term (3 weeks, 1 week of them for the recovery test), long-term (2—3 months) hydrodynamical controlling measurements. Hydrodynamical research of aquifers was based on the method of unstable groundwater flow and on consequent calculation of hydraulic parameters. Hydraulic parameters were calculated from the recovery test curves, using the Theiss equation, modified by

Aquicludes				Aquitards			
Number	Thickness	Σ(m)	%	Number	Thickness	Σ(m)	%
1—9	3—30	3—90	0.0—23.7	1—12	3—21	3—120	0.0—26.8
2—14	5—85	15—393	5.0—39.3	2—49	3—116	25—662	23.7—66.3
4—5	5—107	80—195	15.2—52.1	4—29	3—201	92—796	24.6—87.5
3—13	5—135	72—447	11.0—80.6	5—30	3—68	61—522	14.3—81.0
1	73	73	37.8	1—25	3—208	84—793	62.2—100.0
2—7	8—26	38—102	20.3—22.3	5—24	4—44	48—250	25.7—44.1

Jacob transformation. In the vertical sense the beds were tested separately gradually by single segments (open by jet perforation) from the bottom to the top. The aquifers were thus tested in the depth interval 2503—904 m (except the holes FGB-1/A and FGS-1, where the Pannonian and Pontian sands were also tested in the depth interval 570—275 m). The thickness of single tested segments in the depth interval mentioned was 87—592 m. The thickness of productive aquifers ranged from 34 to 192 m. After the tests on single segments of wells two or more segments were joined by boring through the cement bridge for the purpose of geothermal water exploitation and their thickness was 195—1093 m. The joined segments were tested and hydraulic parameters were calculated.

Hydraulic parameters of aquifers calculated for single or joined tested segments represent the average values for productive aquifers of the respective segments. The calculation of hydraulic parameters and graphical illustration of the course of the recovery tests (Fig. 2) were performed by the personal computer WANG 2200 T by the JACOB program compiled by M. Fendek.

From the recovery tests curves the following parameters were calculated: absolute transmissivity coefficient — T_p (m^3), transmissivity coefficient — T ($m^2 . s^{-1}$), permeability coefficient — k_p (m^2) and hydraulic conductivity coefficient — k_f ($m . s^{-1}$).

The absolute transmissivity coefficient (T_p) is $1.6 . 10^{-10}$—$1.6 . 10^{-13}$ m^3, the transmissivity coefficient (T) $3.6 . 10^{-10}$—$4.9 . 10^{-6}$ $m^2 . s^{-1}$, the permeability coefficient (k_p) $3.21 . 10^{-12}$—$1.95 . 10^{-15}$ m^2 and the hydraulic conductivity coefficient (k_f) $3.88 . 10^{-5}$—$6.0 . 10^{-8}$ $m . s^{-1}$. The distribution of T_p values is in Fig. 4 showing that the values $T_p = 1.6 . 10^{-13}$—$5.4 . 10^{-11}$ m^3 represent up to 85 %. On the basis of the values of the absolute transmissivity coefficient (T_p) the aquifers

were classified in five transmissivity classes (Fig. 5, 6, 7). Following is the interval of T_p values for the classification:
Class 1 — aquifers with $T_p > 10.0 . 10^{-11}$ m^3;
Class 2 — aquifers with $T_p = 5.0—10.0 . 10^{-11}$ m^3;
Class 3 — aquifers with $T_p = 1.0—5.0 . 10^{-11}$ m^3;
Class 4 — aquifers with $T_p = 0.5—1.0 . 10^{-11}$ m^3;
Class 5 — aquifers with $T_p < 0.5 . 10^{-11}$ m^3.

The spatial distribution of aquifers with the above T_p values shows certain characteristic zoning in both the horizontal (Fig. 5) and the vertical sense (Fig. 6, 7). Aquifers with the highest T_p values ($T_p > 10.0 . 10^{-11}$ m^3) are characteristic of the middle part of the central depression, partly or completely bordered on its periphery (towards the depression warnings) with aquifers with gradually decreasing T_p value. The level maps and section show that in the vertical sense the T_p of aquifers decreases with the increasing depth. The zonation is partly disturbed by aquicludes (hydrogeological complex 5). Aquifers in single hydrogeological complexes have the following T_p values:
— aquifers of the hydrogeological complex 2 are characterized by the values of transmissivity classes 1—5 (T_p represented in the whole interval determined);
— aquifers of the complex 3 are characterized by the values of the transmissivity classes 3 ($T_p = 1.0—5.0 . 10^{-11}$ m^3);
— aquifers of the complexes 4 and 6 are characterized by the values of classes 3—4 ($T_p = 0.5—5.0 . 10^{-11}$ m^3);
— aquifers of the complex 5 are characterized by the values of class 5 ($T_p < 0.5 . 10^{-11}$ m^3).

Pressure conditions

Hydrodynamical tests of geothermal water aquifers are based on measurements of hydrostatic pressure at a certain depth level of the well and on the well collar. The measurements result in information about the formation of a pressure depression at single pumping levels, and about pressure conditions in aquifer before the pumping, in the course of recovery tests. The measurement of hydrostatic pressure in geothermal wells is very pretentious on technology because of specific properties of geothermal waters (high temperature, free gas, possible incrustation), and depth demands. Special devices of high precision are inevitable. At the depth 1500 m the values of hydrostatic pressure in the central depression range from 14.5—14.9 MPa. When such value is measured by manometer capable of recording the pressure with the accuracy ± 0.01 %, then the resulting values are charged with the error of the device, differing from the actual value by $\pm 1.10^3$ Pa. When to this error the random errors occurring during manipulation with manometer pulling it out and dropping it to the same depth in the well are added, then the error in the determination of the pressure value can surpass the value of the order 1.10^3 Pa. For example: the value

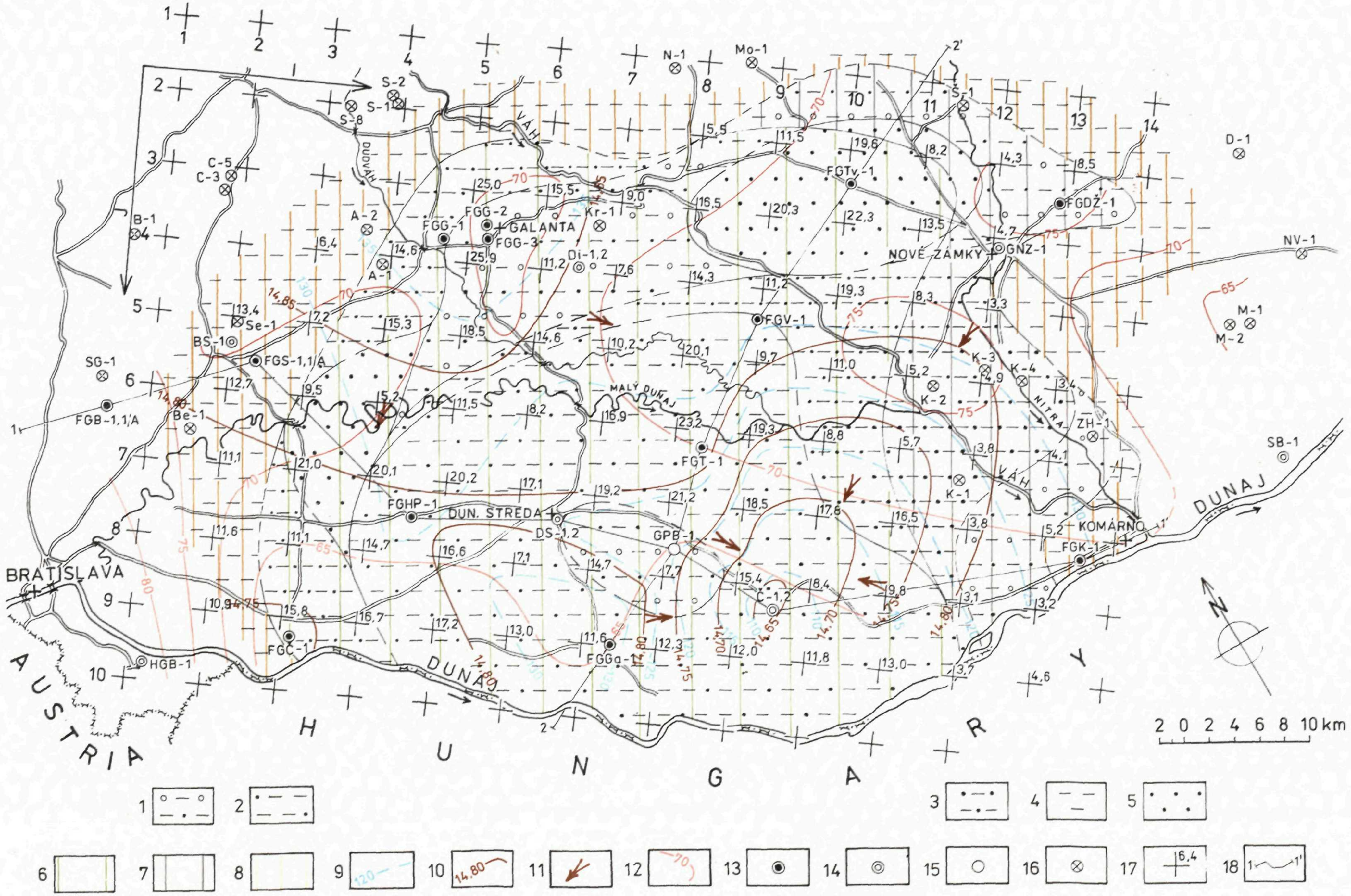

Fig. 5 Hydrogeothermal map of 1 500 m level

1 – hydrogeothermal complex 2 – complex with approximate equilibrium (tolerance ± 13 %) of aquifers and aquicludes (alternating sands, gravels, clays and sandy clays), 2 – hydrogeological complex 3 – with aquicludes dominant over aquifers (alternation of thick – 18–88 m clay beds with thin – 3–12 m sand beds), 3 – hydrogeological complex 4 – with aquicludes dominant over aquifers (alternation of less thick – 3–17 m clay beds with thinner – 3–7 m sand and sandstone beds). 4 – hydrogeological complex 5 – complex of aquicludes (thick clay beds absolutely dominant over scarce thin sand and sandstone beds), 5 – hydrogeological complex 6 – with aquifers dominant over aquicludes (alternating thick and thin sand and sandstone beds with thin clay and marl beds), 6 – transmissivity of aquifers, T_p = 1.0–5.0 . 10^{-11} m^3, 7 – transmissivity of aquifers with T_p = 0.5–1.0 . 10^{-11} m^3, 8 – transmissivity of aquifers with T_p 0.5 . 10^{11} m^3, 9 – hydroisopiestic lines in m above sea level, 10 – isobars in MPa, 11 – course of geothermal water flow, 12 – geoisotherms in °C, 13 – geothermal research well, 14 – geothermal producing well, 15 – geothermic observation well, 16 – structural geological borehole, 17 – calculation nodes, 18 – section line

GÚDŠ EČ 6-1989

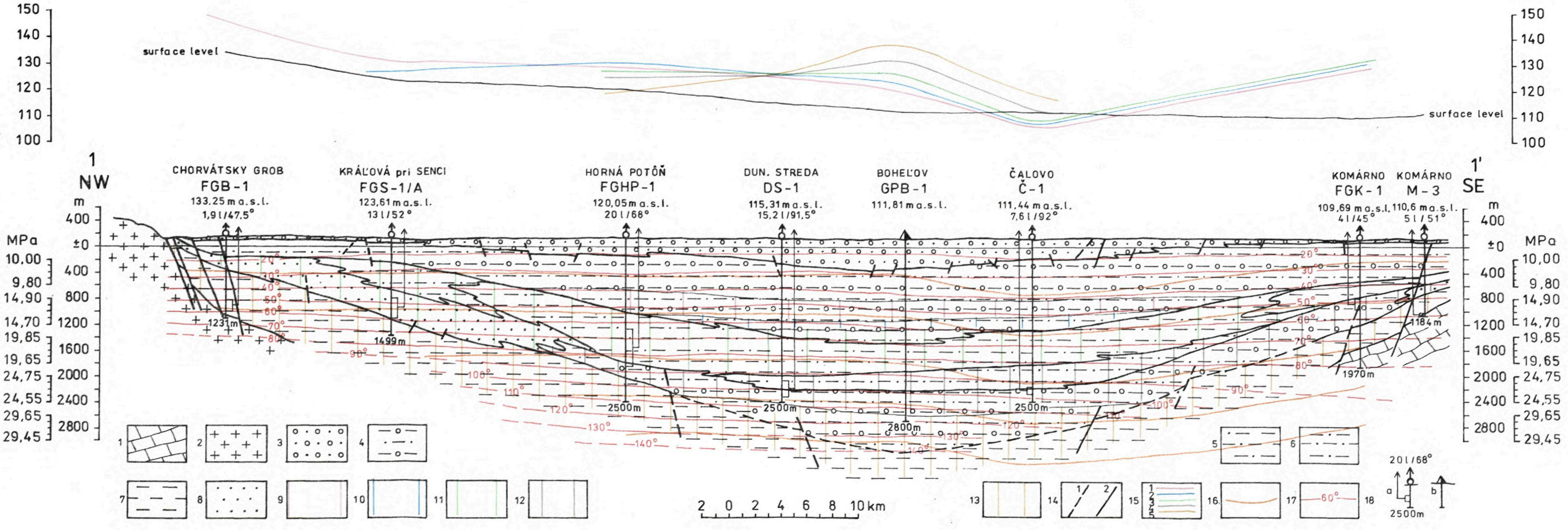

Fig. 6 Hydrogeothermal section 1–1´

1 – Mesozoic – limestones and dolomites, 2 – Paleozoic – granites, granodiorites, 3 – hydrogeological complex 1 – complex of aquifers (sandy gravels and sands, sporadical clays), 4 – hydrogeological complex 2 – complex with approximate equilibrius (tolerance ±13 %) of aquifers and aquicludes (alternating sands, gravels, clays and sandy clays), 5 – hydrogeological complex 3 – with aquicludes dominant over aquifers (alternating thick – 18–88 m clay beds with thin – 3–12 m sand beds), 6 – hydrogeological complex 4 – with aquicludes dominant over aquifers (alternation of less thick – 3–17 m clay beds with thinner – 3 –7 m sands and sandstone beds, 7 – hydrogeological complex 5 – complex of aquicludes (absolutely dominant thick clay beds above scarce thin sand and sandstone beds), 8 – hydrogeological complex 6 – with aquifers dominant over aquicludes (alternation of thin and thick beds of sands and sandstones with thin beds of clays and marls), 9 – transmissivity of aquifers T_p 10.0 . 10^{-11} m^3, 10 – transmissivity of aquifers T_p = 5.0–10.0 . 10^{-11} m^3, 11 – transmissivity of aquifers T_p = 1.0–5.0 . 10^{-11} m^3, 12 – transmissivity of aquifers with T_p = 0.5–1.0 . 10^{-11} m^3, 13 – transmissivity of aquifers with T_p 0.5 . 10^{-11} m^3, 14 – faults: 1 – inferred, 2 – established, 15 – course of piezometric altitude for depth level ^{1}1 000 m, ^{2}1 500 m, ^{3}2 000 m, ^{4}2 500 m, ^{5}3 000 m, 16 – isobars in MPa, 17 – geoisotherms in °C, 18 a – geothermal well with reached bed segment – yield in $l.s^{-1}$ /surface water temperature in °C; depth in m, b – geothermic observation well

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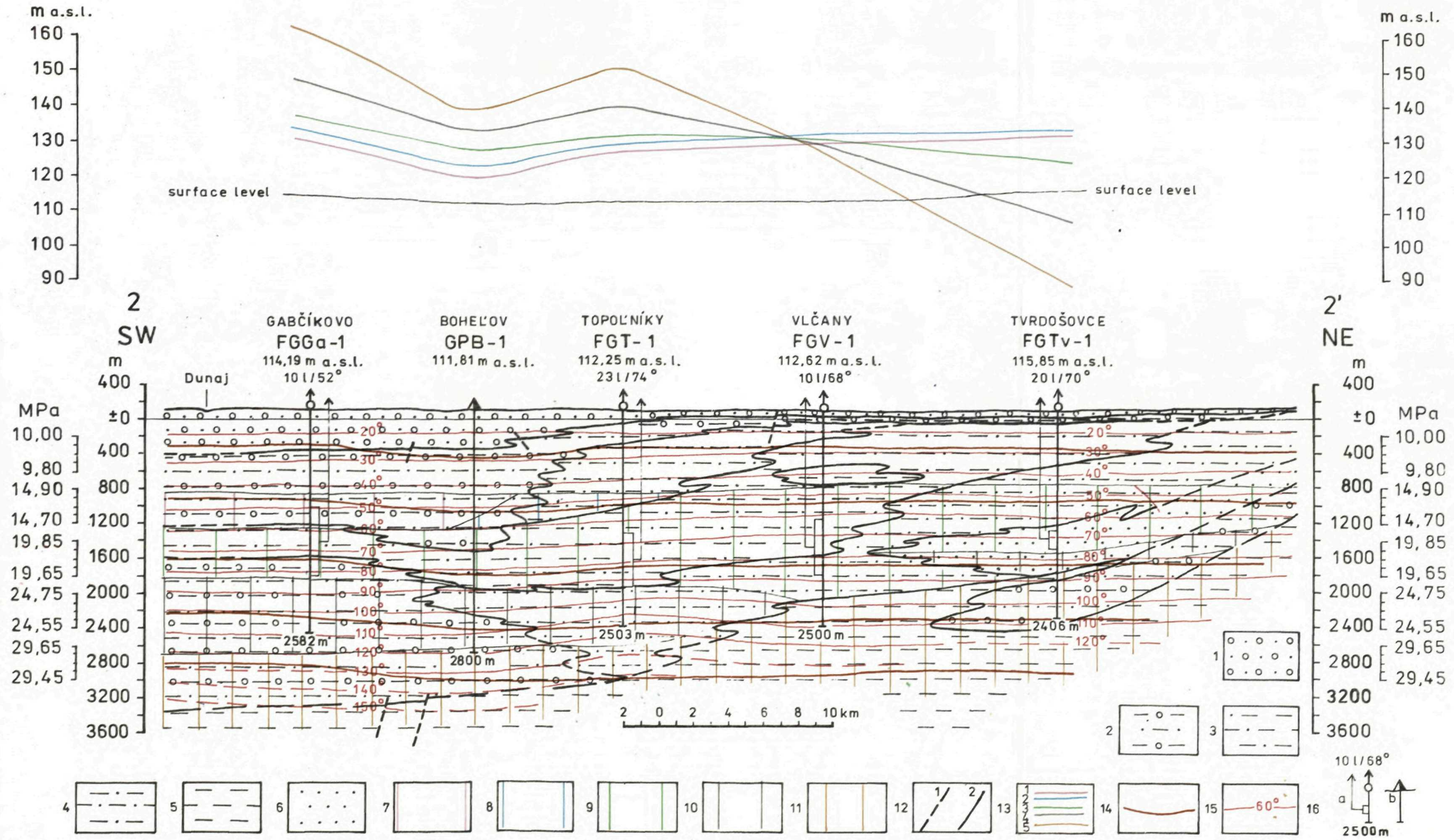

Fig. 7 Hydrogeothermal section 2–2´

1 – hydrogeological complex 1 – complex of aquifers (sandy gravels and sands, sporadical clays), 2 – hydrogeological complex 2 – with approximate equilibrium (tolerance ± 13 %) of aquifers and aquicludes (alternating sands, gravels, clays and sandy clays), 3 – hydrogeological complex 3 – with aquicludes dominant over aquifers (alternating thick – 18–88 m clay beds with thin – 3–12 m sand beds), 4 – hydrogeological complex 4 – with aquicludes dominant over aquifers (alternation of less thick – 3–17 m clay beds with thinner – 3–7 m sand and sandstone beds), 5 – hydrogeological complex 5 – complex of aquicludes (absolutely dominant thick clay beds over sporadical thin sand and sandstone beds), 6 – hydrogeological complex 6 – with aquifers dominant over aquicludes (alternating thick and thin sand sandstones with thin clay and marl clays), 7 – transmissivity of aquifers T_p 10.0 . 10^{-11} m^3, 8 – transmissivity of aquifers T_p = 5.0–10.0 . 10^{-11} m^3, 9 – transmissivity of aquifers T_p = 1.0–5.0 . 10^{-11} m^3, 10 – transmissivity of aquifers T_p = 0.5–1.0 . 10^{-11} m^3, 11 – transmissivity of aquifers T_p 0.5 . 10^{-11} m^3, 12 – faults: 1 – inferred, 2 – established, 13 – course of piezometric altitude for dept level ^{1}1 000 m, ^{2}1 500 m, ^{3}2 000 m, ^{4}2 500 m, ^{5}3 000 m, 14 – isobars in MPa, 15 – geoisotherms in °C, 16a – geothermal well with reached bed segment – yield in $l.s^{-1}$ (surface water temperature in °C; depth in a, b – geothermic observation well

1000 Pa of pressure in geothermal water corresponds to a water column higher than 0.1 m. Thus we get the idea of demands for accuracy of pressure measurements and their comparability within a greater complex. The exploration of geothermal resources of the central depression resulted in plentiful data about pressure conditions. A comparison of measured static values of hydrostatic pressure only in the course of single recovery tests shows that pressure values usually increase with the time value without getting stable. The borehole FGHP-1 is a good example for the depth interval 1804—1394 m where the pressure value was not stabilized even in the time 6 672 000 s. Some examples show that the pressure value repeats in two consequent time intervals at the end of the recovery test (borehole FGV-1, depth interval 1575—1244 m). Other examples show that two equal pressure values may in the last time interval be followed by increased or decreased values (borehole FGV-1, depth interval 2166—2032 m, FGČ-1, depth interval 1549—1195 m). A comparison of pressures measured in one borehole in the same depth interval shows that during the short-term recovery tests the hydrostatic pressure static value decreased. For example in the borehole FGČ-1 in an open segment at the depth level 1731—1409 m the pressure value for the measuring time 156 000 s at the depth 1350 m was 13 252 706 Pa and for the measuring time 468 000 s the pressure value was 13 293 894 Pa. The value difference is 41 188 Pa. There are also reversed cases, like the borehole FGDŽ-1 where in the segment in the interval 1607—1024 m the pressure value at the depth 1000 m for the time 518 400 s was 10 194 100 Pa and for the time 2 260 800 s only 10 057 400 Pa. The difference is 136 700 Pa.

A comparison of hydrostatic pressure static values resulting from long-term recovery tests and from recovery tests performed during annual checking hydrodynamic test in single boreholes shows the decreasing values (for example the borehole FGDŽ-1 where in 1981 the value 10 086 200 Pa was measured, in 1982 the value 10 030 000 Pa and in 1983 the value 10 008 000 Pa) or the increasing values (borehole FGT-1 where in 1975 the value 13 251 726 Pa was measured, in 1976 the value 13 339 985 Pa and in 1977 the value 13 435 110 Pa), or irregularly increasing and decreasing values (e. g. the borehole FGHP-1, where in 1978 the value 13 375 289 Pa was measured, in 1979 the value 13 609 000 Pa, in 1980 the value 13 336 000 Pa and in 1981 the value 13 422 000 Pa).

In spite of that we may state that the course of recovery tests characterized the aquifers tested as an infinitely aquiferous bed in which a quasi-stable state may occur after more than 150 days. A revaluation of hydrodynamic checking tests in boreholes repeated in approximately one year did not reveal any conspicuous decrease of the aquifer pressure which is indicative of a good regeneration ability of the entire hydrogeological structure and of its long life exceptancy in respect of the intermittent thermal water exploitation. The dispersion of hydrostatic pressure static values is regarded as a consequence of variable duration of hydrodynamic tests, systematic and accidental errors in measurements.

The above examples show the great diversity of all the material collected from measurements of hydrostatic pressure static values in the central depression.

And the fact, that in single boreholes the pressure is measured in various levels shows how difficult it is to compile level maps of pressures for the entire area studied, only on the basis of measured hydrostatic pressure static values. The method of getting the pressure value by means of the pressure gradient for the depth level required, is not proper because in the vertical sense remarkable changes of temperature, mineralization and pressure on a greater distance occur and influence the change of the geothermal water specific gravity controlling the change in pressure gradient in various depth intervals which may cause errors in pressure values. It follows that static values of hydrostatic pressures for the same level in all boreholes must be calculated from the values measured. The method of pressure calculation for gas-bearing geothermal water is described by FRANKO—FENDEK (1985). The calculation of hydrostatic pressure static values for the depth levels desirable was based on the facts that the measurements in the entire depression did not reveal any pressure anomalies (the higher or lower values than those of hydrostatic pressure) and that the pressure can also be transported by beds impermeable in respect of the liquid movement. Under these conditions the change in the static value of hydrostatic pressure is only controlled by the changing specific weight of the liquid.

The calculation of the hydrostatic pressure static value for the desirable depth level may be expressed by the equation

$$P_{st} = Pl + Hl \, . \, Gl \qquad (Pa) \tag{1}$$

where Hl (m) is the desirable depth level for which the static value is calculated,

Gl $(N \, . \, m^{-3})$ is the specific weight corresponding to the desirable depth level,

Pl is the static value of hydrostatic pressure on the well mouth for the desirable depth level. It is calculated from the equation

$$Pl = (GO - Gl) \, . \, Hl + PO \qquad (Pa) \tag{2}$$

where GO $(N \, . \, m^{-3})$ is the specific weight corresponding to the desirable depth level,

PO (Pa) is the selected statistic value of hydrostatic pressure on the well collar.

In this way all values of pressures were recalculated on the selected depth levels (Fig. 5, 6, 7). The recalculation shows that all factors influencing specific weight are reflected in piezometric level. Most significant and most conspicuous are spatial changes of mineralization. Piezometric levels for the depth 2500 m on a SW-NE hydrogeothermal section (Fig. 7) may be quoted as an example of a horizontal change. The section shows that whereas in the area of Tvrdošovce the piezometric level is 7.961 m below the surface, in the area of Gabčíkovo it is 32.061 m above the surface. A comparison of T. D. S. in this depth level of the borehole FGTV-1 to mineralization in the borehole FGCa-1 shows that in the first borehole the T. D. S. is more than ten times higher and temperature with a reverse influence upon specific weight is in the borehole FGTv-1 only by 5 °C higher. Naturally the slight increase of temperature cannot eliminate more than tenfold increase of mineralization and therefore the piezometric level in the area of Tvrdošovce is much lower than in the area of Gabčíkovo. If such a comparison is made for the depth level 1000 m, the differences will be less conspicuous: mineralization in the borehole FGTV-1 is 0.71 kg . m^{-3}, temperature 51 °C and in the borehole FGGa-1 mineralization is 1.12 kg . m^{-3}, temperature 44 °C and the piezometric level of well FGTV-1 is 15.230 m and of well FGGa-1 it is 15.559 m above the surface. As for vertical changes in the same boreholes we may state that the mineralization increases with depth only by 1.68 kg . m^{-3} in the borehole FGGa-1 and temperature increases by 83 °C, whereas in the borehole FGTV-1 the values are 4.3 kg . m^{-3} and 81 °C. It follows that piezometric levels for single depth intervals in these boreholes are inverted: they decrease with the increasing depth in the borehole FGTV-1 and increase in the borehole FGGa-1. Differences between piezometric levels and static values of hydrostatic pressure are variable. In the two boreholes mentioned the difference in piezometric level is 300 439 Pa and the difference in static values is only 24 366 Pa i. e. more than ten times smaller. So the value of pressure cannot unambiguously be for a certain level determined only on the basis of piezometric level neither the pressure and hydrodynamical conditions in reservoirs of geothermal waters can be characterized because water does not flow from a higher delivery level to the place of a lower delivery level but it flows from the place of higher pressure to the place of a lower pressure. Generally, in the northern part of the depression the NW-SE flowing course is preserved on all levels. Other courses change in single levels. The term flowing of geothermal water under these conditions denotes the rate of water advance in order 10^{-6} m . s^{-1} representing the distance of 1 km passed in several tens of years. No aquicludes should be presumed in the course of water flow because they can stop it or slow it, prolonging the distance between the points considered.

Geothermic conditions

Geothermic conditions in the central depression are evaluated within the entire Danube Basin (KRÁĽ—LIZOŇ—JANČI 1985). In the most part of the basin the Neogene basement consists of crystalline complexes. Mesozoic sequences are only in the northern parts of the Basin and in the area between Komárno and Štúrovo. Geothermic characteristics of the Danube Basin is based on data from 32 boreholes. To get the maximum amount of information about the heat field we have treated also data on aquifer temperature, resulting from hydrodynamic tests and temperature measurements on the footwall of the borehole. For a complex evaluation of thermal conditions the temperature data by 100 m and geothermal gradient by 100, 500 and 1000 m were statistically treated. Maps of geoisotherms in depths 1000, 1500, 2000, 2500, 3000 and 4000 m below the surface level were compiled for the entire region. All availabe data on Hungarian frontier areas and on boreholes in adjacent areas were considered in the construction of temperature maps. Temperatures to the depths 3000 and 4000 m are extrapolated by a calculation considering thermophysical parameters of the environment in these depths. For the purpose of detailed thermal characteristics of the central depression the average temperature by 100 m are given to the depth 2500 m and by extrapolation to 4000 m. Thermal gradient in the central depression at the depth 0—2500 m is changing in the interval 35.6 °C/km—43.7 °C/km with the average value 39.1 °C/km. The character of thermal field in the depth 1000 m (Fig. 8) is as follow: the average temperature for the entire basin is 47 °C. High temperatures are around elevation structures in the basement near Komárno (55 °C), Štúrovo (50—55 °C), between Chorvátsky Grob and Rusovce (51—57 °C). Low temperatures occurred in a depression between Šamorín, Gabčíkovo and Čalovo (43—44 °C). Eastwards of the zone of lower temperatures the temperature is about 50 °C, westward — around Senec — the average temperature at the depth 1000 m is 49 °C. Towards SE slopes of the Malé Karpaty Mts. the temperature rapidly dropped to about 40 °C. The second anomaly of low temperatures is in the area of the Komárno elevated block (20—24 °C in depth 1000 m). It is due to an intense disturbance of the field by cold karst waters flowing from the Transdanubian Midmountains. The temperature maps to the depth 4000 m show that the termal conditions in the Danube Basin to the depth 1000—1500 m are markedly influenced by the basement elevation with a much higher heat conductivity than in the Neogene complex. A thicker Neogene complex represents a thermal aquiclude, and therefore the temperatures in the central depression are higher than on the basin periphery. It is in maps of temperatures at greater depth. So the highest temperature should be in the centre of the depression with the thickest sediments. But it is not proved by boreholes in Gabčíkovo, Boheľovo and Čalovo. It is due to cold surface waters infiltrating into relatively thick Quaternary sequences and flowing into the centre, resulting in the downward cooling of the rock environment. The anomaly of increased temperatures between Topoľníky, Vlčany, Tvrdošovce, Kolárovo and Dvory nad Žitavou even in the depth 4000 m is indicative of its association with the deep geologic structure. In the geothermal boreholes the drill cores were sampled on approximately every 100 m and the heat conductivity coefficient was determined. The heat conductivity of rocks increased with the growing sand content and decreases with the growing clay content. A detailed study of heat conductivity of single petrographic rock types shows that it is controlled by depth. The relation of heat conductivity to depth is evaluated by the moving average method on the basis of the equation

$$k^{sm}_{i+2} = \frac{k_i + 4k_i + 1 + 6k_i + 2 + 4k_i + 3 + k_i + 4}{16} \qquad (3)$$

where $i = 1 \ldots\ldots\ldots n$

k_{i+j} = heat conductivity $(i + j)$ of the sample, $j = 0, 1, 2, 3, 4$

k^{sm}_{i+2} = smoothed value of heat conductivity by the method of moving averages of 5 neighbouring values

Since the heat conductivity of Neogene sediments depends upon clay contents and deposition depth, we have based the determination of the average conductivity of the Neogene complex in a depth interval upon logs for the determination of clay content. The clay content was determined from the gamma log according to the formula

$$v_i = \frac{G_h - G_p}{G_i - G_p}$$

where G_h = intensity of gamma radiation of bed serched,

G_p = of the bed of pure sand and G_i of the bed of pure clay.

The average heat conductivity in the depth interval explored was determined as the weighted mean in relation to the clayey or sandy fraction.

The average heat conductivity values of Neogene sequences calculated from the above formula were corrected and used for the calculation of heat flows. In cases of boreholes without cores and data on heat conductivity the heat flow was determined according to the statistic data on heat conductivity and their depth relations for single petrographic rock types. The correction on clay content according to gamma log is a method of correcting the heat conductivity of a sandy-clayey complex in relation to the clayey or sandy fraction. Such correction is evidently necessary for the heat flow calculation in Neogene basins (Marušiak—Lizoň 1974) because at random sampling the sand/clay ratio is not preserved and great errors may occur in the determination of average heat conductivity of the Neogene complex and consequently in the heat flow calculation. The heat flow Q in all boreholes was always calculated in two ways: at first as sum of the average heat conductivity and the average thermal gradient according to the equation (5) and then by summation of heat resistivity according to (6). The results of both procedures were almost identic in all wells.

$$Q = k_{str} . G_{str} \qquad (5)$$

where k_{str} is the average value of heat conductivity and G_{str} is the average value of thermal gradient in the bored Neogene complex.

$$Q = \frac{\Delta T}{\sum_i^n \frac{h_i}{k_i}} \qquad (6)$$

where Q is the heat flow in the depth interval explored.

ΔT is the temperature difference in the interval, h_i is the thickness of a bed with the average heat conductivity k_i. A map of heat flow of the Danube Basin (Fig. 8) was constructed from the heat flow values. The minimum heat flow value was in boreholes around Senec (67.70 mWm^{-2}) and the maximum value in boreholes K-2 Kolárovo and FGDŽ-1 Dvory nad Žitavou (87 mWm^{-2}). The average value of heat flow in the central depression is 76 mWm^{-2}.

The heat flows correspond to mean values from the calculation intervals. In almost all boreholes the heat flow increases with depth because the thermal gradient is either constant or slightly increasing with depth, so that heat conductivity also increases with depth. It is a general phenomenon in the central depression and its cause is in the disturbance of the thermal field with infiltrated waters.

Hydrogeochemical characteristics of waters

Spatial distribution of geothermal water chemical composition in the central depression is controlled by depth (Fig. 9, 10, 11). Regularity in depth changes of chemical composition of waters is indicated by:

—the increasing total dissolved solids. The T. D. S. is higher on the depression margin than in its centre. It is due to its dish-like geologic structure. Maybe the mineralization gradient in the centre of the depression was the same as on its margins to about the depth 3000 m;

— the decreasing natrium-bicarbonate component A_1;

— the increasing natrium-chloride component $S_1(Cl)$;

— the decreasing HCO_3/Cl ratio.

In accordance with these regularities the geothermal waters of the central depression may be divided into five groups according to their chemical composition (Tab. 3). The groups represent a continuous hydrochemical field whose character changes continuously — not suddenly — and is controlled by structural-lithological, hydrodynamical, paleohydrogeological, tectonical and other factors.

Group 1 comprises geothermal waters of natrium-chloride type with T. D. S. exceeding 10 $g.l^{-1}$. They are typical of deeper Badenian, Sarmatian and Pannonian aquifers. Their T. D. S. value ranges from 11.63 to 126.40 $g.l^{-1}$. The waters are characterized by a higher portion of the $S_1(Cl)$ component and a lower content or even absence of the A_1 component. The HCO_3/Cl ratio is extremely low. Its highest value is 0.271. It is indicative of hydrochemically closed structure. In this group are also waters with the $S_2(Cl)$ component and without the A_1 component.

Group 2 comprises geothermal waters of the Na-Cl type with T. D. S. 5—10 $g.l^{-1}$. They are associated with Pannonian and Pontian sands and sandstones. In the hydrochemical field model these waters are in aquifers situated higher than in Group 1.

Group 3 represents a transition between Group 2 and 4 and is represented by geothermal waters of the Na-Cl type with the A_1 component exceeding 30 eq% and/or Na-HCO_3 type with the component $S_1(Cl)$ exceeding 30 eq%. The waters are genetically related to Pontian aquifers in semi-closed structures — as indicated by their chemical composition and consequent HCO_3/Cl ratio higher than 1. Their T.D.S. range from 2.72 to 8.73 $g.l^{-1}$ and depend upon their degradation extent (the higher the $S_1(Cl)$ portion, the higher the T. D. S.) and upon the CO_2 content affecting two processes: carbonate dissolution and ion exchange intensified by H^+ ions.

Group 4 comprises natrium-carbon dioxide geothermal waters with T. D. S. 1—5 $g.l^{-1}$. These waters are mostly in Pontian and Dacian aquifers and in "well-washed" Pannonian structures. The Na-Cl component is below 30 eq% and ranges from 1.2 to 24.06 eq%. The HCO_3/Cl ratio is higher and indicative of semiopen structures in many cases.

Group 5 is represented by natrium-bicarbonate waters with T. D. S. up to 1 $g.l^{-1}$ mostly associated with Pontian and Dacian aquifers. The T. D. S. is — besides common mineralization processes — controlled by partial CO_2 pressure in the system. The Na-Cl component is small and depends upon the depth of aquifers and their "washing".

Basing upon the division of geothermal waters into five groups of chemical types associated with geochemical processes geological-geotectonical and hydrogeological conditions at present and in the geological past, the geothermal waters of the central depression are ranged to the following genetic types:

1. Marinogenic geothermal waters,
   a) relict sea waters,
   b) infiltration degraded waters,
   c) high-mineralized waters (brines)
2. Petrogenic geothermal waters
3. Geothermal waters of mixed genesis.

Synsedimentary relict sea waters occur in deeper Miocene sediments of the area studied. There they deposited under the conditions of prevention of the meteoric water infiltration or hypogenic CO_2 influx in the present or in the geological past. The waters are only metamorphosed in the water-rock system heteroionic exchange of Ca^{2+}, Mg^{2+}- Na^+ and the displacement of Ca^{2+} and Sr^{2+} from crystal lattice of solid phase being evidently the main processes. These natural processes resulted in the Na-Cl type of waters including the characteristic Ca-Cl component which is absent even at the minimum value of the A_1 component. It is most likely associated with the ionic strength of the solution, influencing the ion exchange. At the depth 1000 m waters of this type are only in marginal parts of the depression and with the increasing depth they concentrate in the centre of the depression. In the area of Gabčíkovo their probable occurrence at the depth 3500 m is calculated.

Infiltration-degraded marinogenic waters may be divided into two groups according to their chemical composition. Group 1 is represented by preserved waters of the inland sea desalinated by material transport. At present the waters are in closed structures characterized by the Na-Cl type with T. D. S. 5—10 g/l corresponding to paleosalinity of their aquifers. In contrast to relict sea water these waters are associated with shallower sediments. In the eastern part of the central depression the waters occur to the depth 2000 m. Below this depth they concentrate around the centre of the depression.

Group 2 is represented by marinogenic geothermal waters infiltration-

Table 3. Chemical types of geothermal waters

Group No	Depth from to (m)	Stratigraphy	T. D. S. $(g.l^{-1})$	S_1 (Cl)	S_1 (SO_4)	S_2 (Cl)	S_2 (SO_4)	A_1	A_2	$\frac{r HCO_3}{r Cl}$	Chemical type of water[1]
	Central depression of Danube Basin										
1	1124—3048	Pannonian-Badenian	11.6—126.4	76.9—97.2	—	1.4—16.8	—	0.3—22.2	—	0.002—0.29	Na-Cl
2	1473—2460	Pontian-Pannonian	5.1—9.9	74.1—81.6	—	—	0.3—0.8	12.3—23.5	1.5—3.8	0.22—0.34	Na-Cl
3	910—2474	Pontian-Pannonian	2.7—8.8	30.3—65.3	—	—	0.08—0.42	32.1—68.5	1.0—5.4	0.5—2.3	Na-Cl Na-HCO_3
4	904—2303	Dacian-Pontian	1.0—5.0	1.2—24.1	0.23—24.2	—	—	60.4—93.9	0.7—8.0	2.5—61.0	Na-HCO_3
5	276—800	Dacian-Pontian	0.47—0.85	2.2—6.6	0.7—9.4	—	—	63.0—89.5	3.0—24.4	12.6—40.4	Na-HCO_3

[1] Chemical types of water according to Gazda (1971)

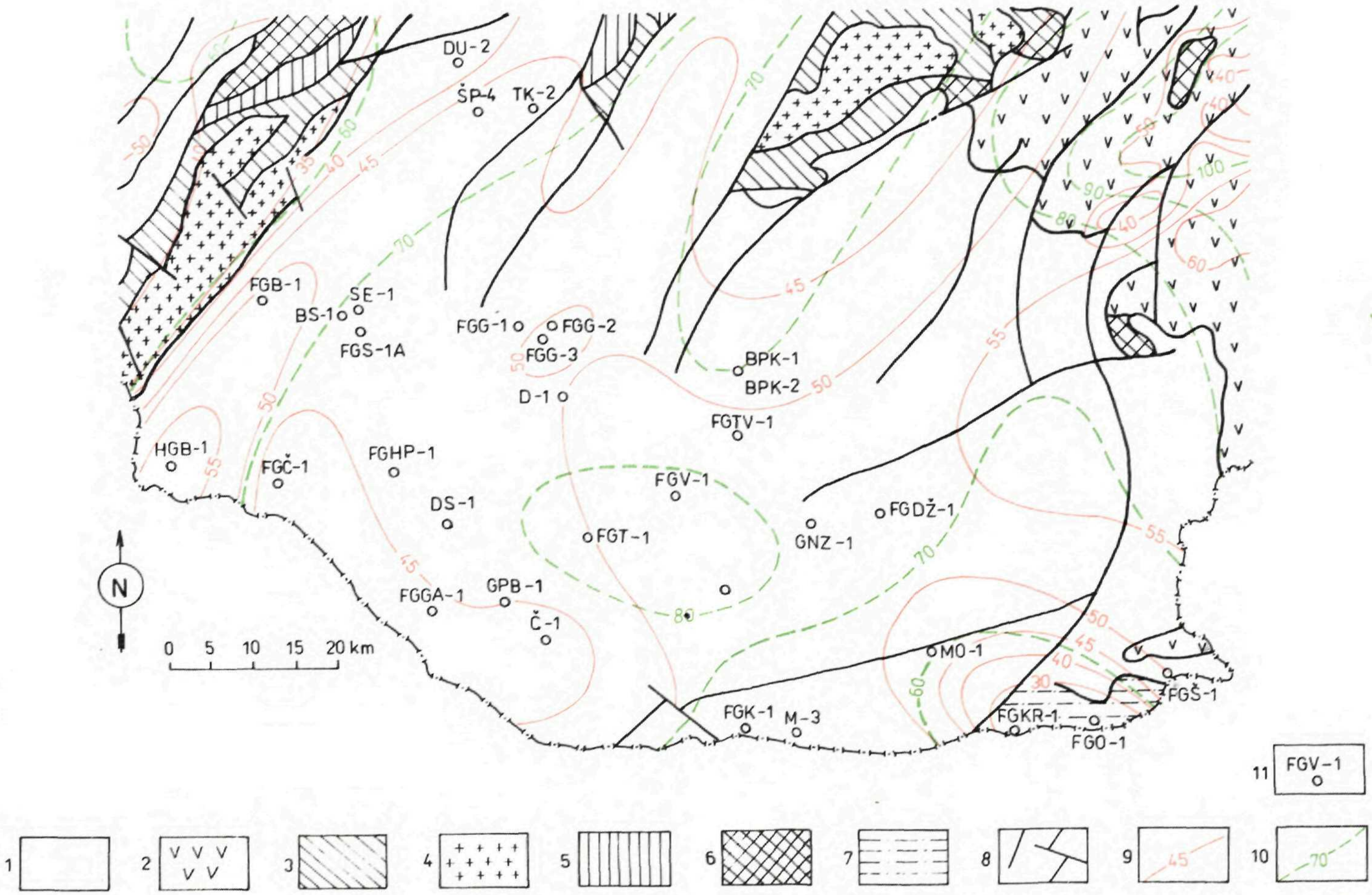

Fig. 8 Map of heat activity in Danube Basin

1 – Neogene, 2 – Neovolcanics, 3–4 – Tatricum: 3 – envelope series; 4 – crystalline complexes, 5 – Fatricum (Krížna nappe), 6 – Hronicum (Choč nappe), 7 – Paleogene, 8 – Fault systems, 9 – Geoisotherms at depth 1 000 m (°C), 10 – Heat flow (mW . m^{-2}), 11 – Wells

GÚDŠ EČ 8-1989

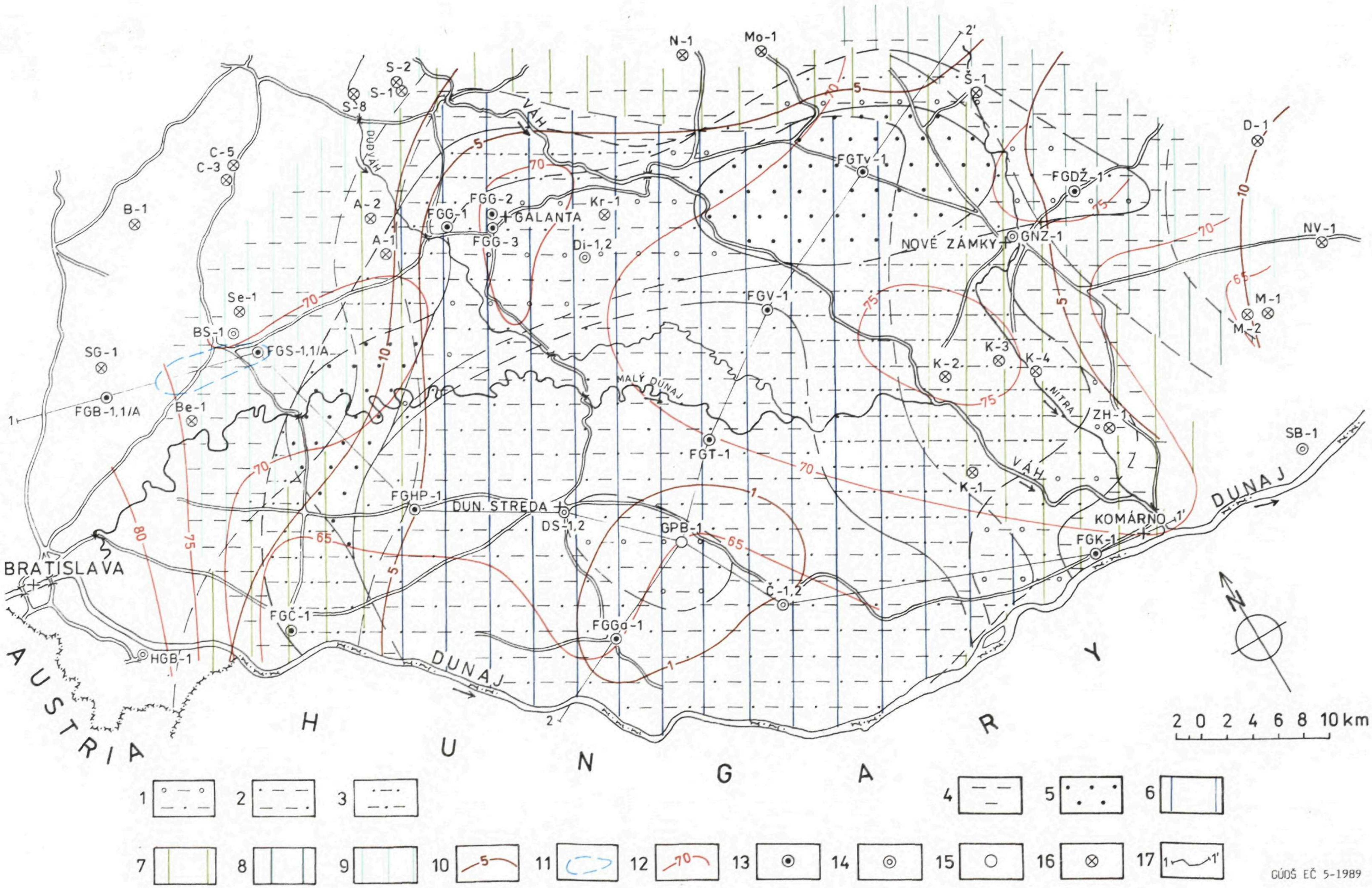

Fig. 9 Hydrogeochemical map of 1 500 m level

1 – hydrogeological complex 2 – with approximate equilibrium (tolerance ± 13 %) of aquifers and aquicludes (alternating sands, gravels, clays and sandy clays), 2 – hydrogeological complex 3 – with aquicludes dominant over aquifers (alternation of thick – 18–88 m clay beds with – 3–12 m sand layers), 3 – hydrogeological complex 4 – with aquicludes dominant over aquifers (alternation of less thick – 3–17 m clay beds with thinner – 3–7 m sand and sandstone beds), 4 – hydrogeological complex 5 – complex of aquicludes (absolutely dominant thick clay beds over thin sand and sandstone beds), 5 – hydrogeological complex 6 – with aquifers dominant over aquicludes (alternating thick and thin sand and sandstone beds with thin clay and marl beds), 6 – natrium-bicarbonate water with T.D.S. $g.l^{-1}$, 7 – natrium-chloride water with A_1 component exceeding 30 eq% or natrium-bicarbonate water with S_1 (Cl) component exceeding 30 eq%, 8 – natrium-chloride water with T.D.S. 5–10 $g.l^{-1}$, 9 – natrium-chloride water with T.D.S. above 10 $g.l^{-1}$, 10 – isolines of T.D.S. of water in $g.l^{-1}$, 11 – anomalous T.D.S. of aquifers in basal Badenian in area of Chorvátsky Grob, Senec and Bernolákovo, 12 – geoisotherms in °C, 13 – geothermal research well, 14 – geothermal producing well, 15 – geothermic observation well, 16 – geological structural borehole, 17 – section line

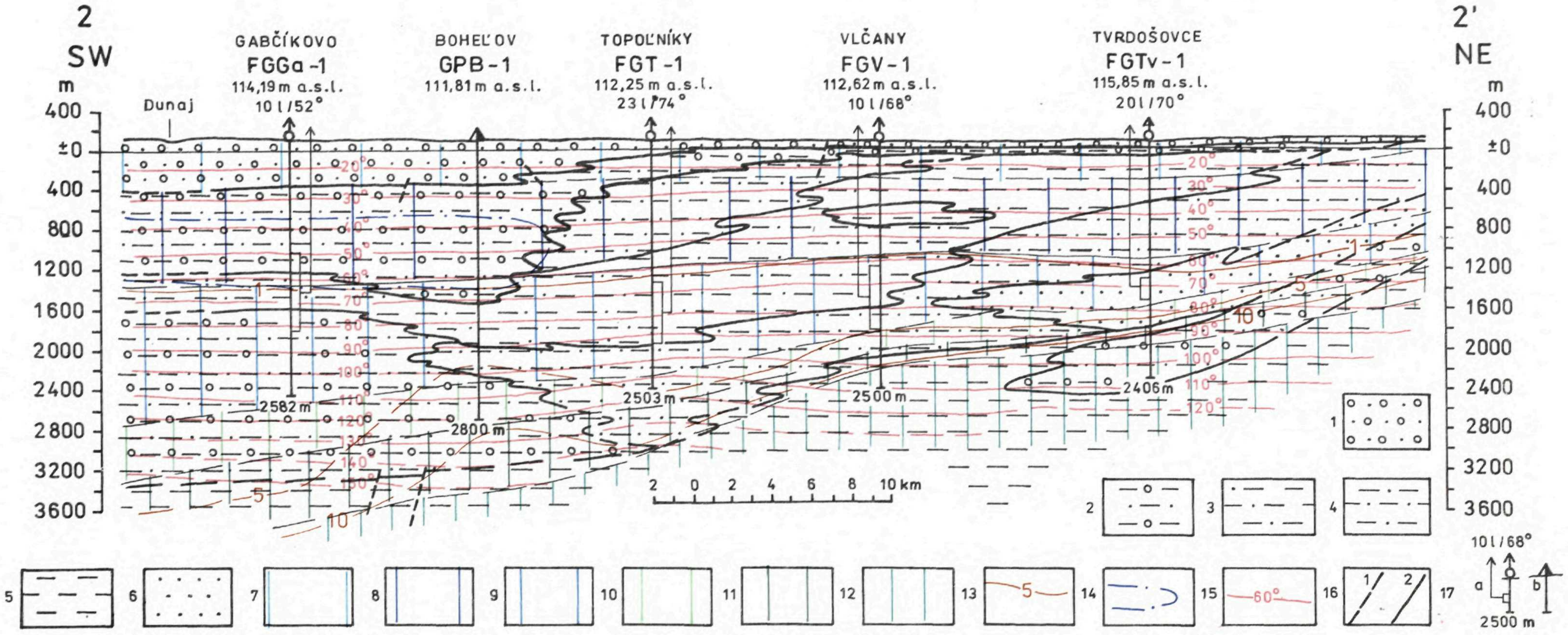

Fig. 11 Hydrogeochemical section 2–2´

1 – hydrogeological complex 1 – complex of aquifers (sandy gravels and sands, sporadical clays), 2 – hydrogeological complex 2 – with approximate equilibrium (± 13 %) of aquifers and aquicludes (alternation of sands, gravels, clays and sandy clays), 3 – hydrogeological complex 3 – with aquicludes dominant over aquifers (alternation of thick – 18–88 m clay beds with thin – 3–12 m sand beds), 4 – hydrogeological complex 4 – with aquicludes dominant over aquifers (alternation of less thick – 3–17 m clay beds with thinner – 3–7 m sand and sandstone beds), 5 – hydrogeological complex 5 – complex of aquicludes (absolutely dominant thick clay beds over sporadical thin sand and sandstone beds), 6 – hydrogeological complex 6 – with aquifers dominant over aquicludes (alternation of thick and thin sand and sandstone beds with thin beds of clays and marls), 7 – calcium-bicarbonate waters of Quaternary sediments, 8 – natrium-bicarbonate water with T.D.S. to $g.l^{-1}$, 9 – natrium-bicarbonate water with T.D.S. 1–5 $g.l^{-1}$, 10 – natrium-chloride water with A_1 component exceeding 30 eq% or natrium-bicarbonate water with S_1(Cl) component above 30 eq%, 11 – natrium-chloride water with T.D.S. 5–10 $g.l^{-1}$, 12 – natrium-chloride water with T.D.S. above 10 $g.l^{-1}$, 13 – isolines of T.D.S. of water in $g.l^{-1}$, 14 – vertical inversion of Cl^- in area of Gabčíkovo, 15 – geoisotherms in °C, 16 – faults: 1 – inferred, 2 – established, 17 a – geothermal well with reached bed segment – yield in $l.s^{-1}$ (surface water temperature in °C, depth in m, b – geothermic observation well

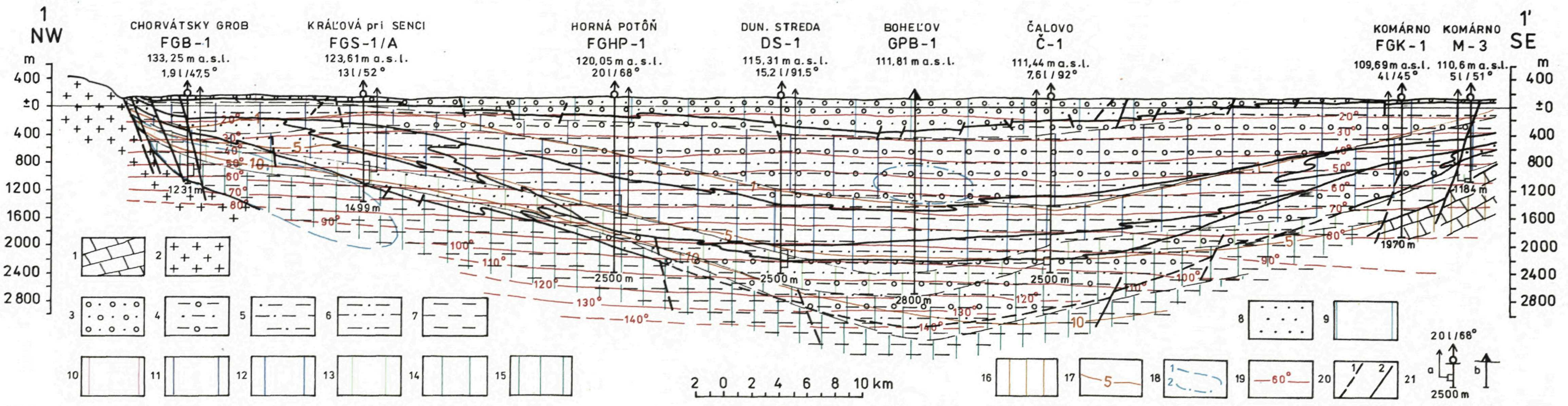

Fig. 10 Hydrogeochemical section 1–1´

1 – Mesozoic – limestones and dolomites, 2 – Paleozoic – granites, granodiorites, 3 – hydrogeological complex 1 – complex of aquifers (sandy gravels and sands, sporadical clays), 4 – hydrogeological complex 2 – with approximate equilibrius (± 13 %) aquifers and aquicludes (alternation of sands, gravels, clays and sandy clays), 5 – hydrogeological complex 3 – with aquicludes dominant over aquifers (alternation of thick – 18–88 m clay beds with thin – 3–12 m sand beds), 6 – hydrogeological complex 4 – with aquicludes dominant over aquifers (alternation of less thick – 3–17 m clay beds with thinner – 3–7 m sand and sandstone beds), 7 – hydrogeological complex 5 – complex of aquicludes (absolutely dominant thick clay beds over sporadical thin sand and sandstone beds), 8 – hydrogeological complex 6 – with aquifers dominant over aquicludes (alternation of thick and thin sand and sandstone beds with thin beds of clays and marls), 9 – calcium-bicarbonate water of Quaternary sediments, 10 – magnesium-bicarbonate water of Quaternary sediments, 11 – natrium-bicarbonate water with T.D.S. to 1 $g.l^{-1}$, 12 – natrium-bicarbonate water with T.D.S. 1–5 $g.l^{-1}$, 13 – natrium-chloride water with A_1 component exceeding 30 eq% or natrium-bicarbonate waters with S_1 (Cl) component exceeding 30 eq%, 14 – natrium-chloride water with T.D.S. 5–10 $g.l^{-1}$, 15 – natrium-chloride water with T.D.S. above 10 $g.l^{-1}$, 16 – mixed water, 17 – isolines of T.D.S. of water in $g.l^{-1}$, 18 – [1]anomalous T.D.S. in aquifers of basal Badenian in area of Chorvátsky Grob, Senec and Bernolákovo, [2]vertical inversion of Cl^- in area of Gabčíkovo, 19 – geoisotherms in °C, 20 – faults: 1 – inferred, 2 – established, 21 a – geothermal well with reached bed segment – yield in $l.s^{-1}$ (surface water temperature in °C, depth in m, b – geothermic observation well

GÚDŠ EČ 10-1989

degraded in the past and in the Recent. They are mostly associated with Pontian aquifers. They are ranged among marinogenic waters because of the "marine" component $S_1(Cl)$ in their chemical composition. They are geothermal waters of the Na-Cl type with the A_1 component above 30 eq% or natrium-bicarbonate type with the $S_1(Cl)$ component exceeding 30 eq%. The waters are distributed around the centre of the depression. At the depth 3000 m they are only associated with the area of Gabčíkovo. They show a considerable mineralizing influence of the rock environment indicative of a generally better "washing" of Pontian aquifers than the Pannonian.

High-mineralized waters (brines) represent the co-called relict salt solutions resulting from local condensation of basinal waters beneath the critical point of NaCl solubility. These waters preserved in hydrogeologically isolated aquifers. Water from the borehole Kolárovo-3 with T. D. S. about 126 $g.l^{-1}$, Br content 564 $mg.l^{-1}$ and Cl/Br ratio 131 is a good example.

Petrogenic geothermal waters of natrium-bicarbonate type are associated with the entire profile of the central depression. Extremely low-mineralized waters (T. D. S. below 1 $g.l^{-1}$) prevail to the depth 300—800 m and low-mineralized waters (1—5 $g.l^{-1}$) dominate to the depth 2500 m in the area of the depression centre. They are most frequent to the depth 1000 m. The borehole FGGa-1 in Gabčíkovo shows an inversion in the increase of T. D. S. with depth, due to lower chlorides concentrations in geothermal waters of the basement. Basing on geochemical interpretation we can state that deeper Pontian sediments in the borehole FGGa-1 are hydrogeochemically more open. Ion exchange (Ca^{2+}-Na^{1+}), in some cases supported by CO_2 influx, is the main mineralization process in the genesis of chemical composition of these waters.

Geothermal waters of mixed genesis are on the SE periphery of the depression around Komárno. They are genetically related to Triassic carbonates sinking to the depth 1100—1700 m along a cascade-shaped system of the Komárno faults. The geothermal waters represent a genetical mixture of Mesozoic carbonate-sulphatogenic waters and infiltration-degraded waters of the overlying Miocene, extending to carbonate complexes in the initial phase of its sea transgression.

According to non-acid gases they are methane-, nitrogenic-, methane-nitrogenic waters, partly with methane dominant. The methane content is highest — 83.67 vol% — in the Na-Cl waters and it increases with depth in well logs. Gases with the highest nitrogene content were in geothermal waters of the borehole FGT-1. Both gases result from biochemical decomposition of organic matter in the presence of micro-organism under favourable living conditions. These waters are characterized by almost total absence of oxygen. The Ar-content ranges from $4.9 . 10^{-5}$ to 2.22 vol%. Among acid gases CO_2 is dominant in geothermal waters. In wells it is associated with higher levels or with structures recharged with CO_2. Gas-factor revealed by separator is in the geothermal waters studied characterized by the range 0.01—4.981. In the soluble gas phase CO_2 is dominant, and in the free phase CH_4 prevails.

Technological characteristics of waters

In respect of geothermal waters exploitation the carbonate-water system is most significant because the disturbed equilibrium is followed by calcite and aragonite incrustation (with admixture of alumosilicates and trace elements). The equilibrium is disturbed when the aquifer pressure is smaller than the total saturation pressure. Then the dissolved CO_2 is released and the biphasis flow-system is formed. The process commences in the bubble point and the carbonate incrustation apears in casing and piping. In aquifers the system is uniphasic in most cases. Practically all conditions are provided for water equilibrium and its oversaturation with calcite — in spite of a low Ca-content in water.

In the central depression there is a general trend towards incrustation in all geothermal waters of the Na-Cl type, associated with deeper Pannonian sediments.

Evaluation of heat-energy potential (HEP)

Prognosis of HEP natural reserves

The natural reserves (static) represent the amounts of geothermal waters and geothermal energy, accumulated in the geologic environment of a hydrogeologic structure —in sands and sandstones. The volume of the delimitated structure is 4031 km^3. Percentage of aquifers in the structure is given in Fig. 1. The average percentage of aquifers in the structure is 34 %. The average value of aquifer porosity is 0.2. Natural reserves of geothermal waters are calculated according to the equation.

$$Q_s = V \, . \, k \, . \, n \qquad (km^3) \tag{7}$$

where Q_s = natural reserves of geothermal waters,
V = volume of the structure (4031 km^3),
k = coefficient of aquifer percentage in structure (0.34),
n = aquifer porosity (0.2)

The values substituted in the equation (7) result in 274.10^9 m^3 representing the natural reserves.

HEP is calculated according to the equation

$$A_t = Q_s \, . \, \Delta t \, . \, C \qquad (J) \tag{8}$$

where A_t = heat energy,
Q_s = natural reserves in kg (1 m^3 ~ 1.000 kg)
Δt = difference between surficial (74 K) and reference (15 K) temperatures of water
C = specific heat capacity of water (4.186 $J \, . \, kg^{-1} \, . \, K^{-1}$)

The values substituted in the equation (8) result in $A_t = 6.76 . 10^{19}$ J. When the water temperature falls down to the average annual air temperature 10 °C, HEP is $7.34 . 10^{19}$ J.

The lowest percentage of aquifers is in the central part of the depression — approximately in the area of Horná Potôň—Gabčíkovo—Vlčany—Diakovce (Fig. 1). It is because of the sands/sandstones ratio decreasing with depth, resulting in fading-out aquifers. The percentage increases towards the depression peripheries.

Prognostic of HEP natural resources

Problems concerning the natural resources (dynamic reserves) in the central depression were for the first time treated by MUCHA (1976) and FRANKO—MUCHA (1975), on the basis of the borehole DS-1 in Dunajská Streda. The geothermal well was situated in a filtration environment which — on the basis of the recovery test course — may be interpreted as an environment with induced infiltration by aquifer leakage from the overlying shallow gravel-sandy groundwater reservoir. The course of recovery tests (Fig. 2) on other boreholes was different from that on DS-1 and the pressure at the end of the test was not stabilized. The course of almost all recovery tests is in the first part steeper than in the second and in the ultimate stage it is milder than in the preceding one. This is indicative of a very slow equalizing of the recovery test course, particularly when the shallower tested aquifer segments are compared with the deeper ones. An analogous situation may evidently exist in the entire depression.

A two-dimensional model for the determination of prognostic resources has been compiled on the basis of the application of a theory (Mucha 1976, Mucha—Šestakov 1982). It is the method of superposition to study the influence of springs (natural or artificial water issues on the surface) and of the recharge (of natural or artificial recharge of aquifers) to the course of the piezometric surface for unstable flowing. The law of superposition is based upon the Laplace equation which may also be solved by the sum of partial solutions, and by the sum of partial solutions multiplied by arbitrarily selected constants. So if the aquifer comprises several springs and recharge then the course of piezometric level of the geothermal water pressure will be equal to the algebraic sum of piezometric levels controlled by single springs or recharge measured from the original state from the course of geothermal water level prior to the spring and recharge activities.

The modelling was made on the personal computer WANG 2200 T by the program "MODEL" compiled by Fendek. The total decrease of pressure (reduction) for the calculation node IJ is calculated for time t as

$$P^t_{IJ} = p^t_{I-1,J-1} + p^t_{I-1,J} + p^t_{I-1,J+1} + p^t_{I,J-1} + p^t_{I,J} + p^t_{I,J+1} + p^t_{I+1,J-1} + \\ + p^t_{I-1,J} + p^t_{I-1,J+1} \qquad (9)$$

where I = No of calculation node in the x direction

J = No of calculation node in the y direction

and single depressions are calculated according to the equation

$$p = \frac{\mu . Q}{4\pi . T_p} . \ln \frac{2.246 . \gamma . T_p . t}{\mu . S . r^2} \tag{10}$$

where Q = yield ($m^3 . s^{-1}$)

μ = dynamic water viscosity ($Pa . s^{-1}$)

T_p = absolute transmissivity coefficient (m^3)

γ = specific gravity ($N . m^{-3}$)

t = time of resource exploitation (s)

r = diameter of a fictitious source in calculation node (m)

S = storativity coefficient (dimensionless number).

The relation for the calculation of total reduction is valid if the interference in the nearest fictitious resources is considered (influence over one pace distance in directions I and J). At present the program enables solutions considering the interference over five step distance in directions I and J, namely the solution of 121 equations for p in each calculation node. When the yields for single time intervals and given maximum depressions are calculated, then the double calculation of the equations is made, because at first the yields are calculated in single calculation nodes, corresponding to maximal depressions, and then the influence of single fictitious resources upon the resource in the calculation node is calculated on the basis of the results obtained. In the case of areal distribution of hydraulic parameters our calculations were based on complex evaluation of recovery tests on the wells and on the present information about their spatial distribution. The mode of selecting the hydraulic parameters will be illustrated by the example of the borehole FGV-1 Vlčany. The evaluation of a recovery test for the depth interval 1575—1244 m is presented in Table 4. The first part of the table shows calculated values of the parameters between single time intervals and their weighted mean. Length of the time interval is used as weight.

We expect the storativity coefficients of aquifers to range from $1 . 10^{-4}$ to $1 . 10^{-6}$. It is proved by the storativity value ($9 . 10^{-5}$ at the first measurement of pressure onset, and $5.5 . 10^{-5}$ at the second measurement), calculated on the borehole FGG-2 serving as an observation well during hydrodynamical tests on the borehole FGG-3 in Galanta.

The maximum drawdown given for the calculation of the yield comes from depressions measured on single wells. There still is some reserve in the calculated yields of single calculation nodes. It is because the static values of aquifer pressures have not been measured and the depressions are smaller. The amount of water pumped from individual calculation nodes was selected so as to prevent irreal values.

The radius of a fictitious source was regarded as a constant r = 0.1 m. The step in the calculation was 6000 m in the direction I and J. In the program the value is recalculated to the radial coordinate according to the equation.

Table 4. Interpretation of the recovery test on the FGV-1 bore-hole in Vlčany for the tested interval 1575—1244 m

Locality: FGV-1 Interval = 1 575—1 244

Q = 8.00000000E-03 RV = .1 TAQH = 71 MIN = 1.6 MTIAZ = 9 652.800036325

1	0	11 747 300	0	
2	300	11 822 700	75 400	
3	600	11 850 200	102 900	MI = 3.94957740 E-04
4	1 800	11 876 200	128 900	
5	3 600	11 885 500	130 200	
6	4 800	11 891 300	144 000	
7	10 800	11 906 900	159 600	
8	14 400	11 911 800	164 500	
9	18 000	11 916 600	169 380	
10	37 800	11 938 800	191 500	
11	99 000	11 960 200	212 900	
12	124 200	11 962 000	214 700	
13	183 600	11 975 200	227 900	
14	262 800	11 981 100	233 000	
15	198 800	11 981 800	234 500	
16	356 400	11 985 000	237 700	
17	383 400	11 986 100	238 800	
18	444 600	12 049 900	302 600	
19	475 200	12 049 900	302 600	

S vs LOG T Thickness of productive formation = 53 m

NUM	POINT	TP (M↑3)	T (M↑2/S)	KP (M↑2)	K (M/S)
2	3	6.329E-12	1.546E-04	1.194E-13	2.918E-06
3	4	1.061E-11	2.593E-04	2.002E-13	4.092E-06
4	5	1.871E-11	4.574E-04	3.531E-13	8.630E-06
5	6	1.245E-11	3.044E-04	2.350E-13	5.743E-06
6	7	1.305E-11	3.190E-04	2.462E-13	6.019E-06
7	8	1.474E-11	3.603E-04	2.781E-13	6.790E-06
8	9	1.148E-11	2.806E-04	2.166E-13	5.195E-06
9	10	8.422E-12	2.058E-04	1.589E-13	3.884E-06
10	11	1.129E-11	2.761E-04	2.131E-13	5.209E-06
11	12	3.163E-11	7.732E-04	5.969E-13	1.458E-05
12	13	7.435E-12	1.817E-04	1.402E-13	3.428E-06
13	14	1.526E-11	3.730E-04	2.880E-13	7.038E-06
14	15	4.605E-11	1.125E-03	8.689E-13	2.123E-05
15	16	1.383E-11	3.380E-04	2.610E-13	6.379E-06
16	17	1.667E-11	4.074E-04	3.145E-13	7.687E-06
17	18	5.829E-13	1.424E-05	1.099E-14	2.687E-07

% from depression = 1

	Depression (PA)	Time (S)	TP (M3)
3	102 900.0	600	1.0610E-11
4	128 900.0	1 800	1.5474E-11
5	138 200.0	3 600	1.3222E-11
6	144 000.0	4 800	1.3213E-11
7	159 600.0	10 800	1.3681E-11
8	164 500.0	14 400	1.3007E-11
9	169 380.0	18 000	1.0714E-11
10	191 500.0	37 800	1.1538E-11
11	212 900.0	99 000	1.5755E-11
12	214 700.0	124 200	1.0868E-11
13	227 900.0	183.600	1.2973E-11
14	233 800.0	262 800	1.6358E-11
15	234 500.0	298 800	1.2945E-11
16	237 700.0	356 400	1.3074E-11

$$r_0 = \sqrt{\frac{\Delta x \, . \, \Delta y}{\pi}} \, . \, 2 \qquad (11)$$

where r_0 = action radius of calculated influence (m)

Δx = step in calculation net in I-course

Δy = step in calculation net in J-course

The value of r_0 depends upon the number of influencing sources in one course.

Fig. 5 shows the calculation net and the yield values in calculation nodes. The values can be obtained from free outflow in the life time of the hydrogeologic structure if no hydraulic parameters change in time.

Prognostic resources are calculated for the depth 1500 m because almost all open intervals of aquifer producing water in the existing wells occur at about this depth level. Most data on hydraulic parameters of aquifers and on chemical-technological properties of water concern the depth level 1500 m. A comparison of data about yields in single intervals shows a gradual stabilization in equal calculation nodes and of total yields. It follows that after continuous even exploitation of fictitious sources in single calculation nodes (after 185 days) the prognostic resources represent 1027 $l \, . \, s^{-1}$ (Tab. 5). The yields in single calculation nodes are comparable with the yields proved by regime monitoring (Fig. 3). This water amount concerns 82 calculation nodes i. e. 82 wells. Seasonal exploitation concerns the winter when the heat energy is utilized for heating in agriculture and housing. This period is followed by regeneration of the geothermal water reservoir. The waters "spared" in winter (consumption being controlled by air temperature) are in summer utilized in swimming pools.

HEP is calculated according to the equation

$$p_t = Q_d \, . \, \Delta t \, . \, C \qquad (W) \qquad (12)$$

where p_t = heat power

Q = natural resources in $kg \, . \, s^{-1}$

Δt = difference between the surface (60 K) and reference temperatures (15 K) of water

C = like in equation (8).

Substitution of respective values into equation (12) results in p_t = about 193 MW (Tab. 5)

Geothermic balance is necessary for the natural resources evaluated and for the area of exploitation.

According to the equation

$$P = F \, . \, q \qquad (W) \qquad (13)$$

where P = heat power of structure,

F = area of structure ($3.744 \, . \, 10^{-9} \, m^2$)

q = average heat flow ($0.076 \, W \, . \, m^{-2}$),

the heat power of the structure is 285 MW. It covers the exploitation of 1027 $l \, . \, s^{-1}$ of geothermal waters with a heat power about 215 MW (Δt = = 60 − 10 = 50 °C) and prevents heat deficit (10 °C = average annual air temperature).

Table 5. Heat — energetic potential of the geothermal resources

Prognoses of HEP	Verified by borehole HEP
geothermal waters with t = 60 °C for depth 1 500 m, seasonal exploitation (185 days) by free outflow	geothermal waters with t = 42.3—91.5 °C
$l.s^{-1}$	
1 027	274
power potential at t reduced to 15 °C	
MW	
193	56
Rough potential	technologically utilizable potential

The results of the model solution are adequate to the present knowledge of the hydrothermal structure explored. The results are presented as prognostic resources.

Conclusions

Among 20 wells are 19 exploitation wells and 1 geothermic observation well (GPB-1 Boheľov, Fig. 1, Tab. 1). It is in the centre of the depression where most exploitation is concentrated. The purpose of the well is observation of the temperature evolution. Nineteen wells determined about 270 $l.s^{-1}$ of exploitable geothermal waters with temperature ranging from 42.3 to 91.5 °C. Thermal-energetical potential of these wells, calculated according to the equation (12) is about 55 MW (Tab. 5). About 137 MW (Tab. 5) should be proved by exploratory-exploitation wells. The difference about 753 $l.s^{-1}$ i.e. 137 MW is gradually proved by wells in accordance with regional demands.

Geothermal power of the wells is utilized for the heating of 3 buildings (a sports-hall in Topoľníky, and other buildings in Dunajská Streda, restaurant with lodging-house in Diakovce), 20 ha of glass-houses, and about 35 swimming pools. In Galanta a housing-quarter comprising 1100 flats, a hospital and a pensioner house will be heated.

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Methods of Research and Evaluation of Geothermal Energy Reserves in a Fissure-Karst Setting of the Slovak Part of the Vienna Basin

Abstract. The work deals with the methods of the research and evaluation of geothermal energy reserves in a fissure-karst setting with the example of geothermal water structures in the Slovak part of the Vienna Basin. The methods of drilling, drill-logging measurements, hydrogeological testing of drillholes and hydrodynamic tests have made it possible to obtain geological, hydrogeological, geothermic and hydrochemical data, the synthesis of which enabled us to form a scheme of the spatial distribution of thermal waters and geothermal energy reserves. The geothermal energy reserves (prospective and prognostic) have been evaluated for reinjection exploitation. The thermal-energetic potential of prospective reserves represents 511 MW and that of prognostic resources amounts to 268 MW.

Introduction

One of the areas where geothermal waters have been investigated as well as geothermal energy reserves have been evaluated in a fissure-karst setting is the Slovak part of the Vienna Basin (A. REMŠÍK al 1985). This territory is situated among the Morava river and the Malé Karpaty Mts. and the line Senica—Dojč—confluence of the Morava and Dyje rivers (Fig. 1). The geothermal waters of this area are associataed with Triassic dolomites and limestones of the Choč nappe and higher nappes underlying the Neogene sediments of the basin. The Triassic carbonates, as aquifers of geothermal waters, are characterized by a fissure-karst permeability.

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Research methods

Before the realization of the geothermal research, Lakšár and Šaštín elevations have been evaluted from the viewpoint of geothermal water prospecting (the original idea was to investigate only these two structures of the Vienna Basin). The evaluation presented a synthesis of prior geological, geophysical, hydrothermal and hydrochemical data and knowledge which resulted in a proposal of geothermal research whose aim was the recognition of the spatial distribution of geothermal waters and geothermal energy reserves. The research geothermal drillhole RGL-1 was located in Lakšár elevation (depth 2100 m, yield of free outflow 24 $l.s^{-1}$, water temperature 77 °C) and the other RGL-2 in Šaštín elevation (depth 2605 m, yield of free outflow 12 $l.s^{-1}$, water temperature 73 °C). The drillholes revealed qualitative and quantitative parameters of the rocks and waters. These data, together with those from petroleum drillholes throughout the Slovak part of the Vienna Basin, have been complexly evaluated and geothermal energy reserves have been calculated.

As regards drilling, drill-logging measurements and hydrodynamic tests, their research methods are similar to that of the porous setting of the Pannonian Basin which is dealt with in other work (see O. Franko et al. 1989). The differences, which will be described below, result from a different character of the aquiferous setting (lithology, type of permeability etc.).

In slightly fractured Triassic dolomites and limestones, non-core rotary drilling with clayey drilling fluid has been successfully applied. Problems arise in intensely tectonically fractured Triassic carbonates where drilling fluid is partially or entirely lost (partial or entire colmatage), drillhole walls are unstable (trapping and burial of drill strings), drill core is difficult or even impossible to obtain. Frequently, even special ingredients (feathers, cut straw etc.) are of no use, the drillhole has to be prematurily cased and one profile of casing is thus lost, which is undesirable in geothermal praxis. Reaching of the projected aim of drilling depends mainly on technical ability and therefore the depth range capacity of any drill rig should always be higher than the depth of the projected drillhole. Drilling with clear water turns out successful.

After drilling a complex of logging measurements has to be carried out. Their objective is to distinguish rock lithology, identify permeable stretches and evaluate their permeability. In a carbonate setting, the optimum complex of logging measurements is following: neutron-neutron logging, gamma-gamma logging, density and acoustic logging, self-potential measurements, resistivity methods (laterolog, microlog), cavernometry, resistivimetry, thermometry and inclinometry. The basis for the identification of fractured and/or permeable zones are the first two methods together with acoustic logging, the other are supplementary.

Hydrodynamic tests, which serve us for the determination of parametres of aquifers, waters and drillholes, were carried out, in comparison with tests in porous setting (see O. Franko et al. 1989), in a reduced time span (7 to 9 days) but their contents, except for long-term hydrodynamic test, remained unchanged. Triassic carbonates were tested from top to bottom and permeable stretches were fitted by a drilled perforation (15—20 %) filter. The application of jet perforation in permeable zones is not suitable here (cementation of fissures and fractured zones). At first, as early as during drilling, the upper parts of aquifers were tested. Later, after the drilling had finished, also their deeper parts were tested. In a 2100 deep drillhole at Lakšár elevation, three depth intervals of collectors (Triassic carbonates occur at a depth of 1242—2100 m) were thus tested.

Evaluation methods

Geothermal water structures

Geothermal water structures were determined on the basis of the geological-tectonic structure, distribution of collectors and character of waters (type of waters, mineralization etc.). In space, the individual structures are confined by these marginal conditions — at the top by the Neogene sedimentary complex, which as a whole represents an impermeable overburden of the structures, laterally by the boundaries of collector distribution or by faults, at the bottom — their boundaries are problematic due to oblique and subvertical dip of the beds (permeable stretches have been identified as deep as 4400 m) and because of the lack of data.

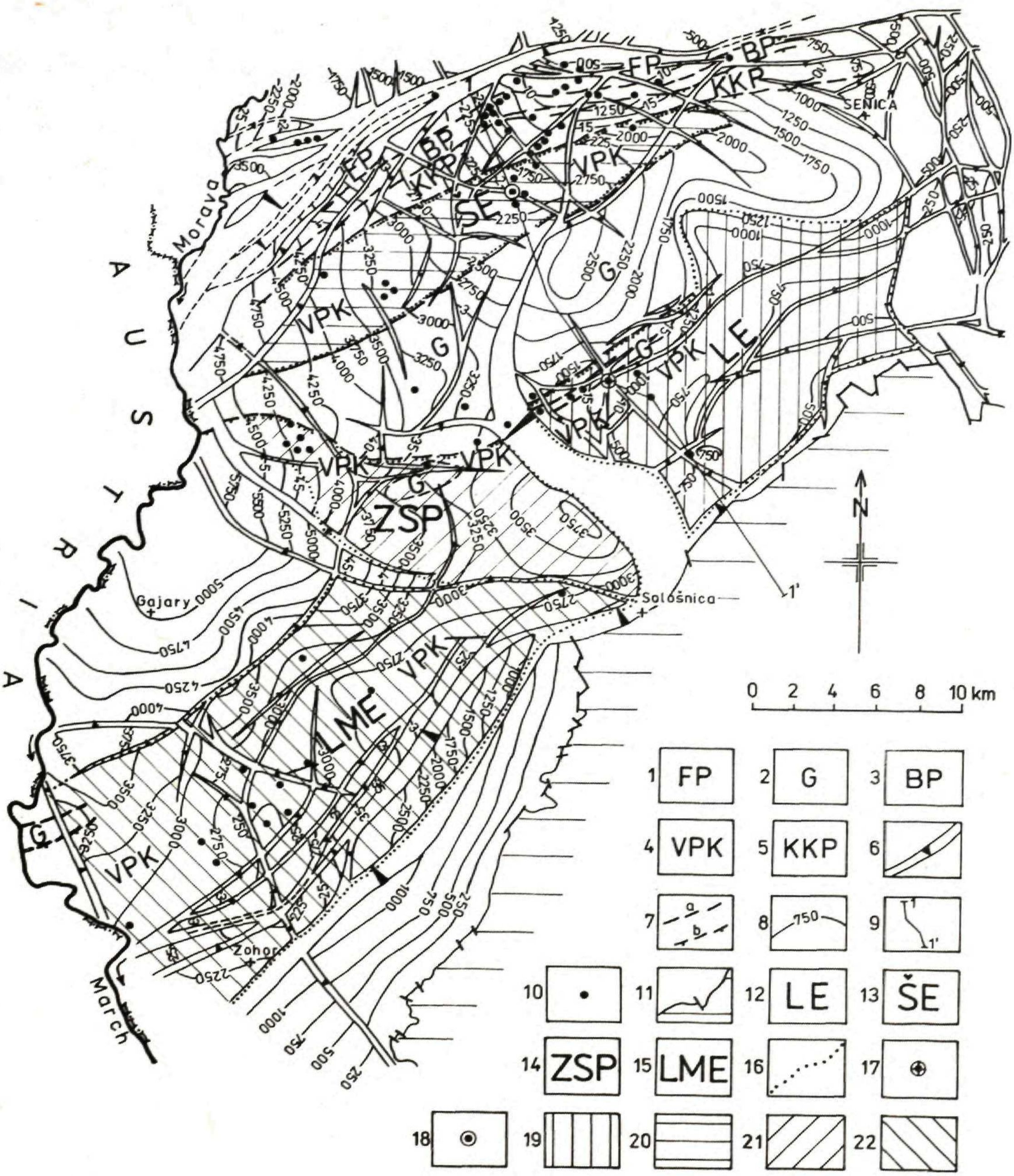
In the Slovak part of the Vienna Basin, four geothermal water structures have been determined (Fig. 1). The waters are associated with the already-described Triassic carbonates as well as overlying Eggenburgian clastics which form together a single hydrogeological unit. The structures occur at depth of 500—4500 m and contain waters with reservoir temperature of about 40—140 °C.

Lakšár elevation. It represents an elevated belt of complex internal structure, elongated in the NE-SW direction. The W and N dipping surface (roof) of the structure lies at a depth of 500—1600 m. In the upper parts of the structure, in a depth interval 500—2500 m, geothermal waters with reservoir temperature of approximately 40—90 °C occur.

The Šaštín elevation with an adjacent S-W and N-S sunk belt. As a whole it forms an elongated SW-NE trending zone with a marked elevation in the vicinity of the RGL-2 drillhole. The surface of the structure occurs at a depth of 1600—4500 m and geothermal waters with reservoir temperature of 65—140 °C are present here.

Závod—Studienka sunken belt. It represents an E-W trending sunken zone. The surface of the structure lies at a depth of 3000—4500 m and it hosts geothermal waters with reservoir temperature of 95—140 °C.

Láb—Malacky elevation with adjacent sunken blocks extends in the southern part of the area and forms a SW-NE trending elevated belt which is transversally divided into Láb and Malacky partial elevations. The surface of the structure


A U S T R I A
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occurs predominantly at a depth of 2150—3800 m and geothermal brines with deposit temperatures 90—140 °C are accumulated in it.

From the structural viewpoint, in the sense of O. FRANKO's (1975) division of hydrogeological structures, Lakšár elevation is an open structure — Fig. 2 (this concerns also the upper parts of the Triassic carbonate complex, i. e., it has an infiltration, accumulation and spring area — hydrogen-sulphide springs at Plavecký Mikuláš and Plavecký Peter). Šaštín elevation represents a semiopen structure (it has an infiltration and accumulation area, whereas a spring area is absent), Závod—Studienka sunken belt and Láb—Malacky elevation are close structures (contain only accumulation areas).

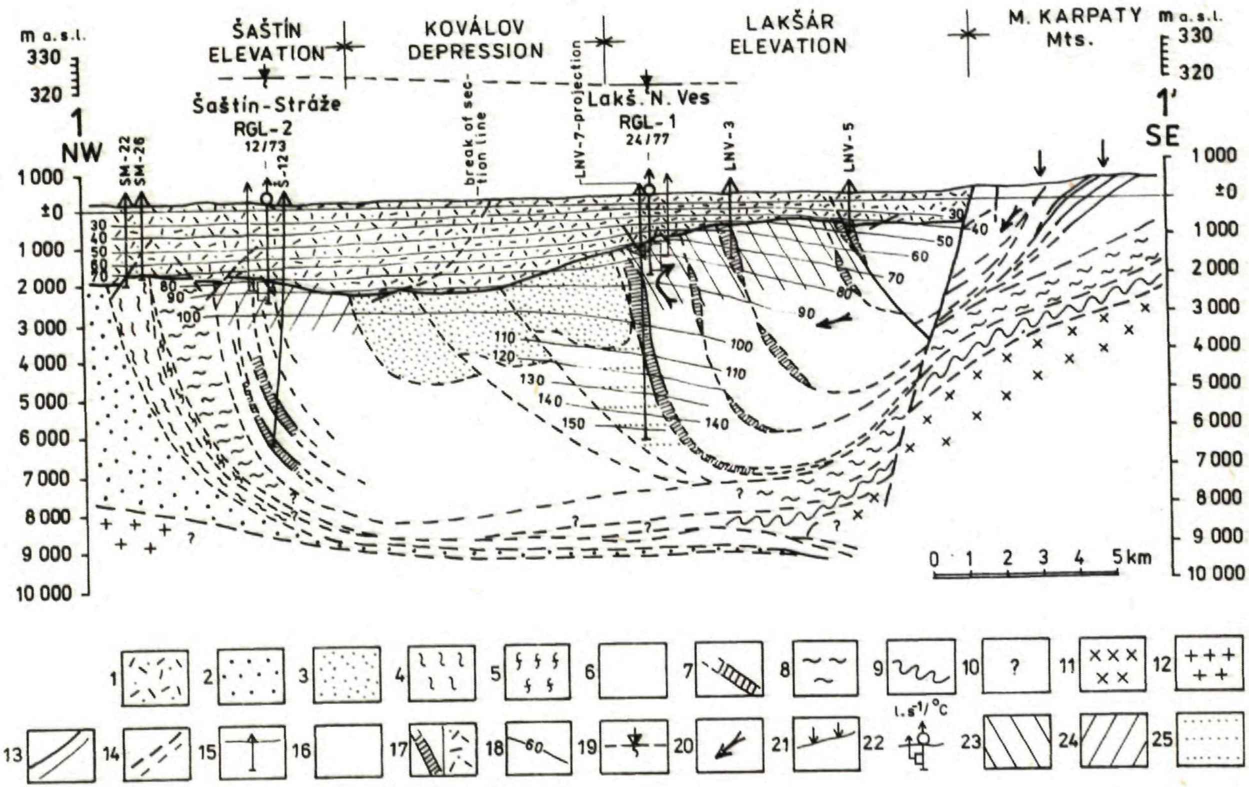
Hydraulic parameters

In Lakšár and Šaštín elevations, hydraulic parameters, which represent basic characteristics reflecting hydrophysical properties of collectors (yield, permeability and others), have been calculated from the curves of recovery tests using Theis equation modified by Jacob approximation. Their values are given in Tab. 1 and do not characterize the whole Triassic carbonate complex but only its fractured zones. The collectors have been tested in a depth interval of 1242—2570 m, the length of individual intervals ranged from 80 to 833 m. Within these intervals, 1—12 productive stretches, 5—19 m thick, occurred and their total thickness varied from 5 to 120 m. In other structures, hydraulic parameters have been determined by logging in petroleum drillholes.

The highest, downward decreasing permeability is typical of Lakšár elevation Triassic dolomites (kp = $1.02—2.88 \times 10^{-12}$ m^2 — Tab. 1). The permeability of Triassic dolomites in Šaštín elevation ($k_p = 6.82 \times 10^{-14}$ m^2) and Závod—Studienka sunken belt ($k_p = 9.74 \times 10^{-14}$ m^2) is lower by more than one order. On the contrary, their porosity (3.18 % and 3.02 %, respectively), which is similar,

←

Fig. 1 Structures and chemistry of geothermal waters (using material of J. KYSELA et al. 1983) Explanations — Geology: 1 — Flysch Belt, 2 — Senonian and Paleogene of "Gosau type", 3 — Klippen Belt, 4 — Triassic-Lower Cretaceous of nappes overlying the Križna nappe, 5 — Križna and/or Klape nappe, 6 — faults, 7 — supposed boundaries (a — lithological, b — of nappe overthrusts), 8 — isobaths of pre-Neogene basement, 9 — section line, 10 — structural-geological or exploration petroleum drillholes, 11 — margin of Malé Karpaty Mts. Hydrogeology: collectors-Triassic dolomites and limestones of nappes overlying the Križna nappe (fissure and/or karst-fissure permeability), 12—15-structures of geothermal waters, 12 — Lakšár elevation, 13 — Šaštín elevation with adjacent SW and NE sunken belt, 14 — Závod—Studienka sunken belt, 15 — Láb—Malacky elevation with adjacent sunken blocks, 16 — delimitation of geothermal water structures, 17 — research geothermal drillhole RGL-1, 18 — research geothermal drillhole RGL-2. Hydrogeochemistry: 19 — halogenic waters S_1(Cl) [S_2(SO_4) — 16—24 eq%, A_2 above 5 eq%], T. D. S. 5—7 g . l^{-1}, 20 — metamorphosed marinogenic waters S_1(Cl) [A_1 to 20 eq% and A_2 to 5 eq%], T. D. S. 7—15 g . l^{-1}, 21 — metamorphosed marinogenic waters S_1(Cl) [A_1 to 15 eq%, and A_2 to 5 eq%], T. D. S. 15—25 g . l^{-1}, 22 — brines formed by seawater evaporation and water-rock interaction S_1(Cl) [S_2(Cl) from 0.4 to 23.4 eq%], T. D. S. (90)100—130 g . l^{-1}.



m a.s.l.
330
320
1
NW
ŠAŠTÍN ELEVATION
KOVÁLOV DEPRESSION
LAKŠÁR ELEVATION
M. KARPATY Mts.
m a.s.l.
330
320
1'
SE
Šaštín-Stráže
RGL-2
12/73
Lakš. N. Ves
RGL-1
24/77
SM-22
SM-26
Š-12
break of section line
LNV-7-projection
LNV-3
LNV-5
1 000
±0
1 000
2 000
3 000
4 000
5 000
6 000
7 000
8 000
9 000
10 000
0 1 2 3 4 5 km
l.s-1/°C
1 2 3 4 5 6 7 8 9 10 11 12
13 14 15 16 17 18 19 20 21 22 23 24 25

Table 1 Hydraulic parameters of collectors

Structure	Aquifers	Production or investigated[+] interval (m)	Coefficient of absolute transmissivity T_p (m^3)	Coefficient of permeability k_p (m^2)	Hydraulic conductivity k_f ($m.s^{-1}$)	Mean porosity (%)
Lakšár elevation (RGL-1)	Triassic dolomites	1270—1275 1435—1562 1450—2010	$1.44 . 10^{-11}$ $7.47 . 10^{-11}$ $9.16 . 10^{-11}$	$2.88 . 10^{-12}$ $2.08 . 10^{-12}$ $1.02 . 10^{-12}$	$7.77 . 10^{-5}$ $5.79 . 10^{-5}$ $2.87 . 10^{-5}$	1.66[+]
Šaštín elevation (RGL-2)		2005—2570	$8.18 . 10^{-12}$	$6.82 . 10^{-14}$	$2.17 . 10^{-6}$	3.18
Závod-Studienka sunken belt		4123—4435	—	$9.74 . 10^{-14}$	—	3.02[++]
Láb-Malacky elevation (L-115)	Triassic limestones	2575—4125*	—	$6.56 . 10^{-15}$	—	0.7—1.2[++]

[+] From drillhole LNV-7 (1930—2263 m), [++] according to drill logging

←

Fig. 2 Hydrogeothermal section of Lakšár and Šaštín elevations (using material of J. KYSELA et al. 1983) Explanations: — Geology: 1 — undivided Neogene, 2 — Flysch Belt, 3 — Cretaceous and ? Paleogene of Gosau type, 4 — Klippen Belt,5 — ?Klape unit (nappe), 6 — nappes overlying the Krížna nappe (Choč, Veterník, Havranica, Jablonica and other-? alpine), 7 — dark schistose claystones and sandstones-Lunz beds (Carnian), 8 — Krížna and Vysoká nappes, 9 — Tatric Mesozoic, 10 — occurrence and/or continuation of tectonic unit is problematic (unknown), 11 — Tatric crystalline, 12 — ? crystalline and sedimentary mantle of Bohemian Massif, 13 — proved tectonic and lithological boundaries, 14 — supposed tectonic and lithological boundaries, 15 — structural-geological or exploration petroleum drillhole. Hydrogeothermy: 16 — collectors of geothermal waters (fissure and/or karst-fissure permeability), 17 — aquicludes, 18 — geoisotherm, 19 — piezometric head of geothermal waters (metres above sea level), 20 — supposed direction of ground water movement, 21 — infiltration area, 22 — research geothermal drillhole with water-bearing interval, yield/temperature of water. Hydrogeochemistry: 23 — halogenic waters $S_1(Cl)$ [constituent $S_2(SO_4)$ — 16—24 eq%, A_2 above 5 eq%], T. D. S. 5—7 $g.l^{-1}$, 24-metamorphosed marinogenic waters $S_1(Cl)$ [constituent A_1 to 20 eq% and A_2 to 5 eq%], T. D. S. 7—15 $g.l^{-1}$, 25 — marinogenic and/or variably metamorphosed waters $S_1(Cl)$ with T. D. S. 35—44 $g.l^{-1}$, and/or $S_1(Cl)$ with constituent $S_1(SO_4)$ — 1—21 eq% with T. D. S. 10—25 $g.l^{-1}$.

is higher than that of Lakšár elevation Triassic dolomites (1.66 %). The permeability of Triassic limestones of Láb—Malacky elevation determined by microscopic research is relatively low ($k_p = 6.56 \times 10^{-15}$ m^2). Other evaluations of "fissure porosity" indicated its higher values.

Pressure conditions

Pressure conditions are characterized on the basis of pressure changes during recovery tests in the RGL-1 and RGL-2 drillholes. In the course of recovery test in the RGL-1 drillhole, pressure quickly increased in all tested intervals (in 8 minutes the pressure rose by more than 96 % of the total measured depression and after 40—120 minutes equal static values of hydrostatic pressure were measured), which is characteristic of open and semiopen structures. The maximum saturation pressure value 2.198 MPa has been calculated for production interval at a depth of 1450—2010 m, with yield 24 l . s^{-1} and it corresponds to gas bubble point at a depth of 211.6 m. The sum of gaslift and thermolift is 383 604 Pa, which represents 59 % of the total measured depression and immediate pressure static value at well collar is 0.98 MPa.

During the recovery test in the RGL-2 drillhole, which lasted 132.5 hrs — 11 times longer than the pumping test, there was achieved no stationary state of pressure. For the maximum yield — 12 l . s^{-1} (production interval at a depth of 2005—2570 m), the saturation pressure value of 3.35 MPa has been calculated, which corresponds to the gas bubble point value 351.9 m. The sum of gaslift and thermolift is 624 797 Pa, which represents 28.5 % of the total measured depression. The immediate pressure static value at the drill collar is 2.014 MPa.

Piezometric head of geothermal waters of Lakšár and Šaštín elevations is almost the same (319 and 324 m above sea level, respectively) and corresponds to hydrostatic pressure.

Geothermic conditions

The thermal field is characterized by a considerable variability of its thermal activity. Its course correlates with the distribution and/or trend of elevation structures in the pre-Neogene basement, in which its highest activity is concentrated. Two anomalies of increased temperatures — Láb—Malacky elevation with temperatures above 50 °C and Lakšár elevation with temperatures above 60 °C in a depth of 1000 m (Fig. 3) are characteristic. Temperatures at Šaštín elevation are less conspicuous. South of Lakšár elevation, the temperature abruptly falls to 32 °C recorded in the R-1 drillhole. This decrease in temperature is due to cooling caused by ground water advancing from the Malé Karpaty Mts. into the basin's sedimentary filling. Within Lakšár elevation — in its upper parts (discovered at depths of 1070—2300 m), the thermal field is affected by convection heat transfer. The existing anomaly due to convection

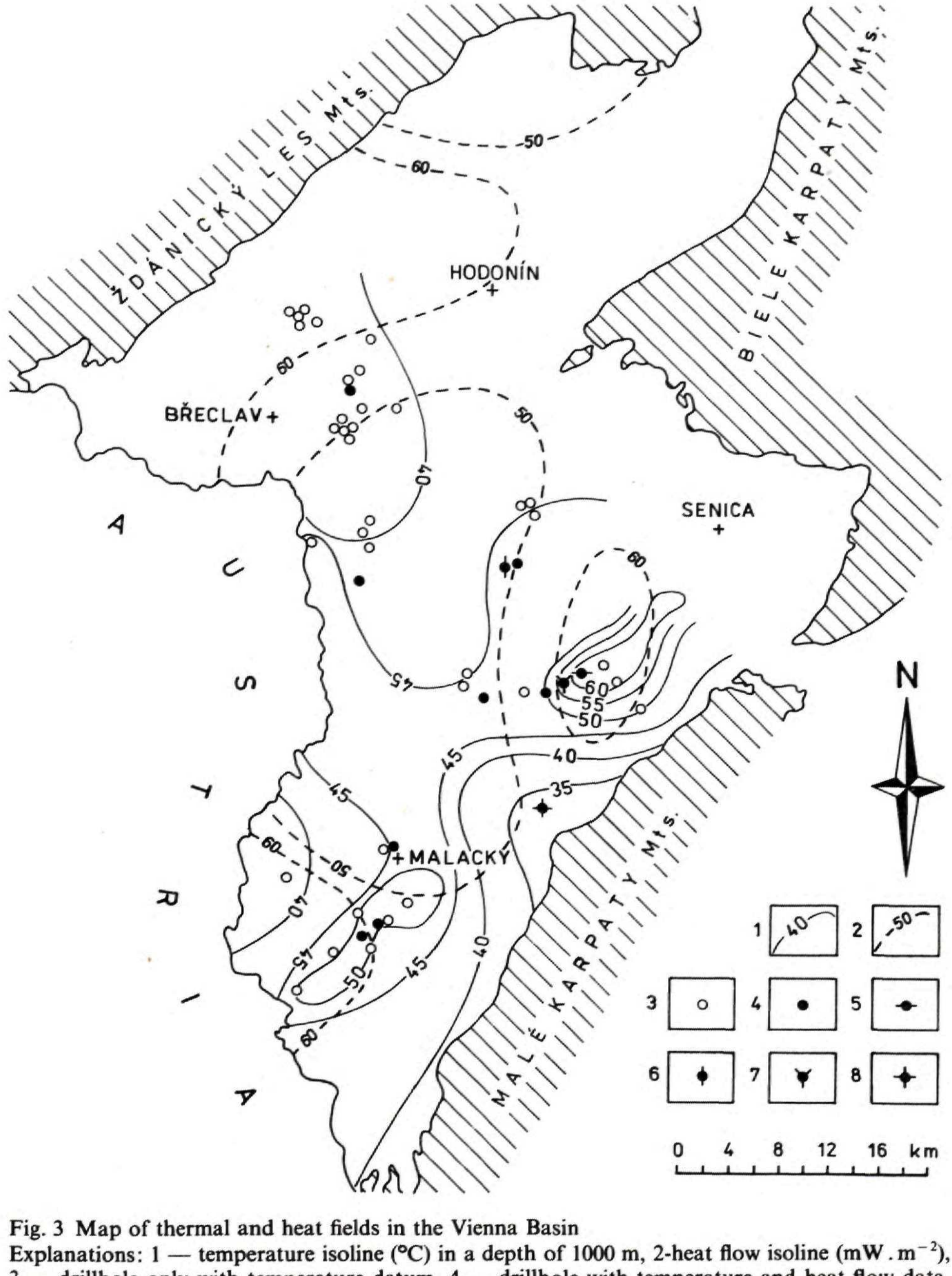


Fig. 3 Map of thermal and heat fields in the Vienna Basin
Explanations: 1 — temperature isoline (°C) in a depth of 1000 m, 2-heat flow isoline ($mW \cdot m^{-2}$), 3 — drillhole only with temperature datum, 4 — drillhole with temperature and heat flow data, 5 — research geothermal drillhole RGL-1, 6 research geothermal drillhole RGL-2, 7-drillhole LNV-7, 8 — drillhole R-1.

heat transfer discovered by the LNV-7 drillhole gradually fades out from a depth of 2300 m and entirely ends at a depth of 4400 m, under which the thermal field is undisturbed. At the same time the convection heat transfer comes to its end and conductive transfer takes place. In Láb—Malacky and Šaštín elevations the thermal field is undisturbed.

Mean temperature in the Vienna Basin at a depth of 1000 m is 43 °C, 2000 m — 80 °C and 3000 m — 98 °C. Average geothermic gradient in the interval 0—1000 m represents 34 $K . km^{-1}$ and in general decreases downward.

The basin's Neogene sedimentary filling (predominantly clays and sandstones) is characterized by average heat conductivity 1.43—2.52 $W . m^{-1} . K^{-1}$. Triassic dolomites and limestones have heat conductivity from 1.91 to 3.7 $W . m^{-1} . K^{-1}$ with mean value of 3.1 $W . m^{-1} . K^{-1}$.

Heat flow in the Vienna Basin varies from 45 to 62 $mW . m^{-2}$ averaging 54 ± 9 $mW . m^{-2}$. New analyses indicate that heat flow values are higher by approximately 10 $mW . m^{-2}$.

Hydrochemical characteristics of water

The Vienna Basin is characterized by Na-Cl-type geothermal waters with various shares of other constituents expressed in Palmer—Gazda's indexes (e. g., $S_2(SO_4)$, A_1, A_2, etc.) up to 25 eq% and T. D. S. 5 to 130 $g . l^{-1}$ (Tab. 2).

Genetically, the waters are marinogenic, metamorphosed with the rock environment (e. g., waters of Lakšár and Šaštín elevations are metamorphosed by the contact with anhydrites) and remained either preserved or thickened and/or degraded. Evaporation of sea water resulted in the formation of geothermal brines in Láb—Malacky elevation. In deep parts of Lakšár elevations, "original" sea waters, isolated from those in the upper parts of the structure by an impermeable shale formation, have been preserved. In other structures the sea waters are degraded. The genesis of waters in the uppermost part of Lakšár elevation is unclear. On the basis of chemical composition of waters from the RGL-1 drillhole they may be degraded marinogenic waters but oxygen and hydrogen isotope analyses ($\delta^{18}O = -10.76$ to -19.95 ‰, $\delta D = -74.2$ to -81.0 ‰) suggest meteoric origin of these waters, i. e., the water would be petrogenic.

In geothermal waters of Lakšár and Šaštín elevations, hydrogen sulphide amounting to 29.7—234.0 $mg . l^{-1}$ has been identified. Its origin is related to biochemical reduction of sulphates present in the waters.

From the point of view of geothermal water exploitation, the system carbonates-water and chemical composition of waters are very important. Under reservoir conditions the system carbonates—water is stable (water is slightly oversaturated with calcite and dolomite or they are in an equilibrium state). During exploitation the equilibrium is disrupted (pressure decreases below the value of saturation — two-phase currents above gas bubble point) and conse-

Table 2 Chemical types of geothermal waters

Depth from-to (m)	Stratigraphy	T. D. S. ($g.l^{-1}$)	S_1 (Cl)	S_1 (SO_4)	S_2 (Cl)	S_2 (SO_4)	A_1	A_2	$\frac{HCO_3}{Cl}$	Chem. type of water*
1116—2002	Eggenb.—Trias.	5.3—6.8	58.6—71.6	0.2—12.6		16.7—25.4		6.2—16.0	0.1—0.26	Na-Cl
2005—2780	Eggenb.—Trias.	8.3—15.5	59.8—85.2	7.6—19.2			2.0—18.8	2.6—5.2	0.1—0.7	Na-Cl
4455—5000	Triassic	14.4—22.8	69.3—89.3	5.6—15.1			1.4—13.3	2.2—3.8	0.06—0.22	Na-Cl
5400—5950	Triassic	34.7—43.8	87.2—91.6			2.2—3.0		0.8—2.0	0.01—0.02	Na-Cl
2145—3000	Triassic	90.0—129.7	84.0—98.8		0.6—15.2	0.2—0.6		0.2—0.6	0.01—0.06	Na-Cl

* Classification according to S. GAZDA (1971)
Note: Palmer-Gazda's indexes are expressed in eq%

Table 3 Geothermal energy reserves in structures

Structure	Water temper. (°C)		Thermal difference* (°C)	Geothermal water amount ($l.s^{-1}$)	TEP of reserves (MW)	
	reservoir	surficial			prospective	prognostic
Lakšár elevation	80	75	60	950	—	239.00
Šaštín elevation with adjacent SW and NE belt	90—120	83—100	68—85	325	75.17	28.56
Závod-Studienka sunken belt	125	100	85	390	139.76	—
Láb-Malacky elevation with adjacent blocks	115	100	85	825	295.85	—
Total				2490	510.58	267.56

* Thermal difference = surficial water temperature—reference temperature (15 °C)

quently incrustations are formed in casing and distribution network. Intensive corrosion of casing and network is due to highly mineralized Na-Cl-type waters containing H_2S.

Evaluation of thermal-energetic potential (TEP) of natural reserves

Reserves in individual structures have been evaluated as regards the type of structure concerned, their exploitation and environment protection during exploitation. In all structures the geothermal energy reserves have been evaluated for exploitation by means of reinjection by model solution carried out by the calculator WANG 2200T according to the program HEAT (M. FENDEK). The structures have been covered by a quadrangular network with a 2 km step (distance between exploitation and reinjection drillholes) and input parameters for modelling of velocity, pressure and thermal field have been given in individual calculation points. TEP of prognostic reserves was calculated in structures where research geothermal drillholes had been realized. In other structures and areas where only data from petroleum drillholes were available, TEP of prospective reserves was calculated.

TEP of prognostic reserves of Lakšár elevation represents 239 MW (exploited and reinjected amount 50 l . s^{-1}, water temperature 75 °C, thermal difference from reference temperature 60 °C, cooling manifestations as far as 2 km after 50 years) and that of Šaštín elevation 28.56 MW (exploited and reinjected amount 25 l . s^{-1}, water temperature 83 °C, thermal difference 68 °C, cooling manifestations as far as 2 km after 110 years). TEP of prospective reserves in the adjacent NE and SW belt of Šaštín elevation amounts to 75.17 MW (the parameters are the same as those in the preceding case, except for water temperature which is 83—100 °C). In Závod—Studienka sunken belt and Láb—Malacky elevation with adjacent sunken blocks, TEP of prospective reserves is 435.41 MW (exploited and reinjected amount 30 l . s^{-1} and 25 l . s^{-1} respectively, water temperature 100 °C, thermal difference 85 °C, cooling manifestations as far as 2 km after 65 years).

Total TEP of prospective resources of the Vienna Basin structures represents 511 MW and that of prognostic reserves is 268 MW (Tab. 3).

Conclusions

The methods of drilling (non-core rotary drilling with clayey fluid and interval core taking), logging measurements (radioelectric, electric, thermometric and technical methods), hydrogeological tests of drillholes (1—3 tested intervals from top to bottom), hydrodynamic tests (application of non-stationary flow methods) chosen for the purposes of geothermal research and evaluation of geothermal energy resources have made it possible to obtain geological (lithology, stratigraphy, tectonics), geophysical (electric conductivity and/or electric resistivity of rocks, temperature of rock setting etc.), hydrogeological (yield, temperature, pressure, hydraulic parametres of collectors etc.) and hydrochemical data (chemical composition of waters, gases and rocks). The synthesis of all these data, including those from petroleum drillholes, allowed us to construct a scheme of spatial distribution of geothermal waters and geothermal energy resources in the Vienna Basin structures.

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IGOR MODLITBA—MÁRIA KOVÁČIKOVÁ

Engineering-geological investigation of anthropogenic deposits

Abstract. The authors present classification and definition of anthropogenic deposits, applicable to the engineering-geological evaluation of the environment and of foundation soils. The methods of regional investigations are illustrated with the example of the Bratislava region and adjacent areas.

The complex data file about waste disposals in the form of an alphanumerical register is presented as the basic research method of investigation. The method was tested on a model region and will now be obligatory for the engineering-geological investigation of anthropogenic deposits in Slovakia. The results are recorded in maps 1 : 10 000 and serve as complex data for the protection of environment from contamination and devastation of landscape, and as a basis for optimal utilization of the landscape system in respect of human existence.

Introduction

The present time is characterized by an extreme interest in all problems concerning the environment. Specialists and the public are equally interested in the purity of atmosphere, surface water, soil, groundwater a. o. Among problems concerning the environment devastation the problem of the wastes representing one of the groups of anthropogenic deposits, is paid a great attention.

At present the human building activity cannot be concentrated only to areas utilized for agriculture or forestry. It is necessary to utilize so far inattractive areas — like the places of anthropogenic deposits. Their optimal utilization must inevitably be based on information about their composition, distribution, thickness and properties.

The study of anthropogenic deposits is forced not only by the necessity of the environment protection but also by the increasing frequency of accidents on building sites and constructions due to the underestimation of engineering-geological properties of anthropogenic deposits. In most cases it is a displaced material or the filling of excavated areas. It is very difficult to identify the

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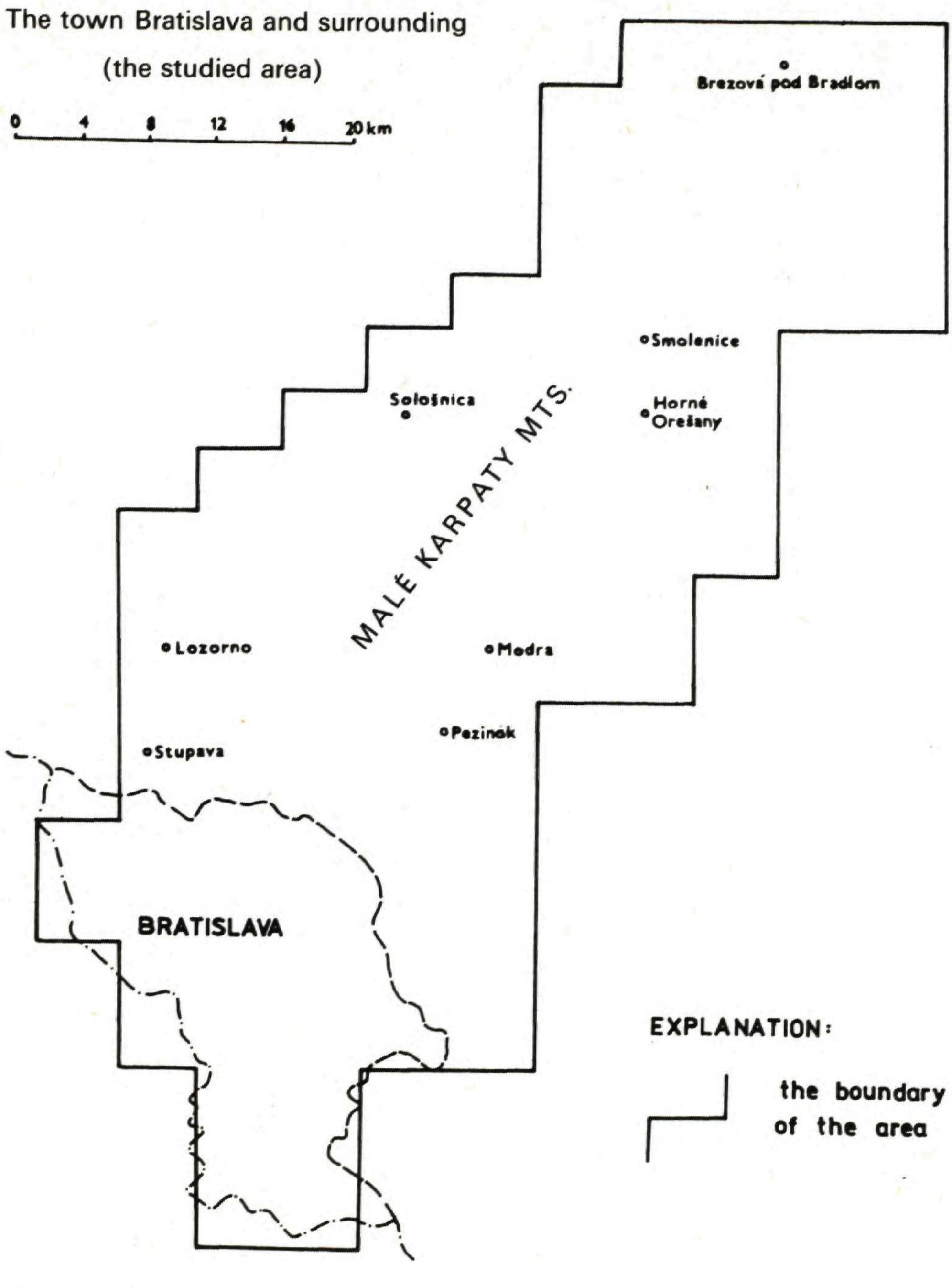
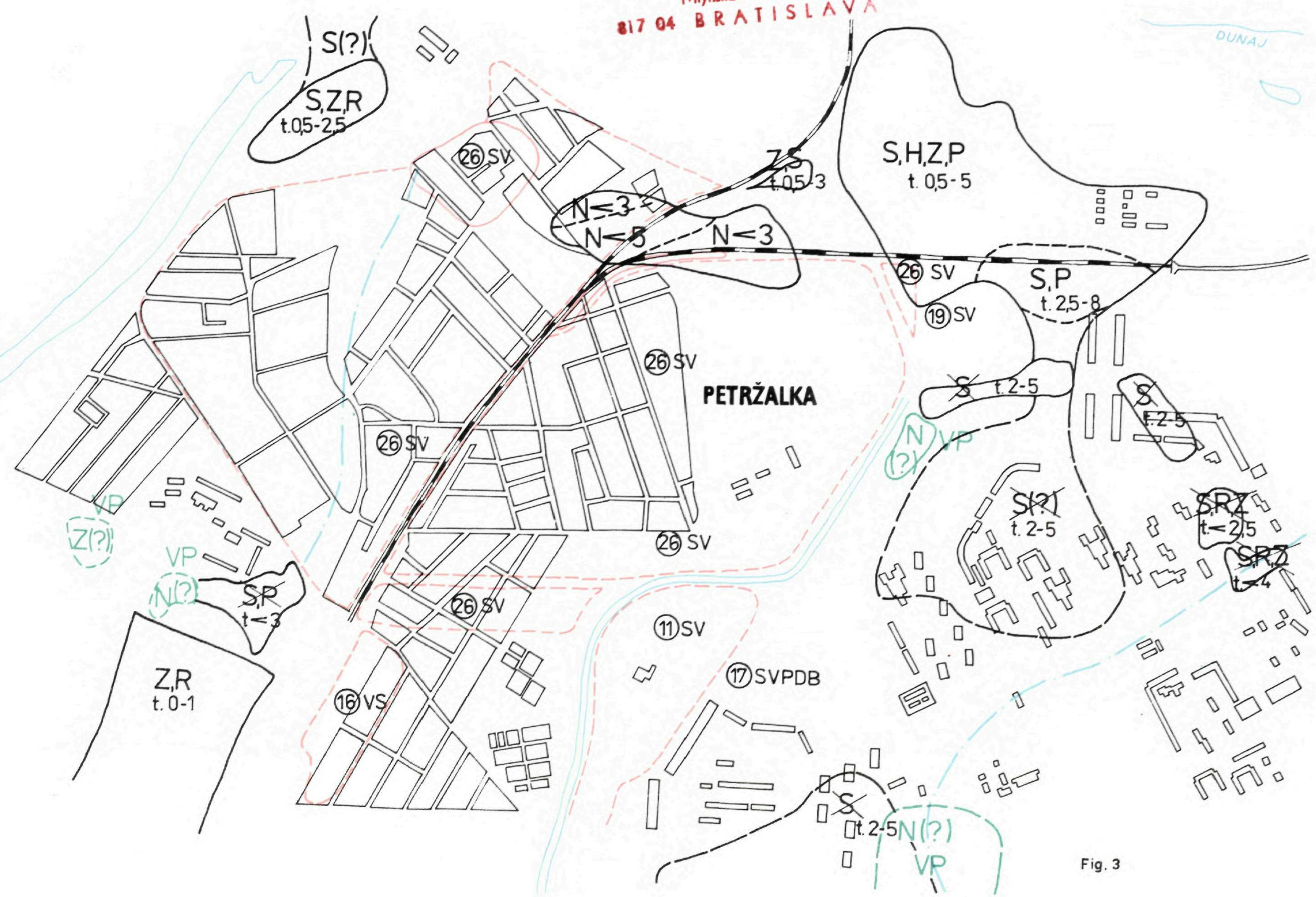


Fig. 1 Location of the investigation of antropogenic deposits

The map of covered antropogenic deposits



0 0,5km

EXPLANATION :

the area of the waste deposit

the area of the temporary waste deposit

⑦ the number of the waste deposit

VS the composition of the waste deposit

Z,R t.2-5 the area with the covered antropogenic deposits

the type of deposit:
- S - communal material
- H - rock material
- Z - soil material
- P - industrial material
- R - demolish material
- N - undefined material

t.2-5 t<5 thickness of the antropogenic deposits

S t.2-5 the area with the antropogenic deposits fully or partly removed

VP N(?) Z(?) the old open pits filled or probably filled with the antropogenic deposits

the axis of the oxbow of the Danube river

Fig. 3

The inventory of the waste deposits (a sample)

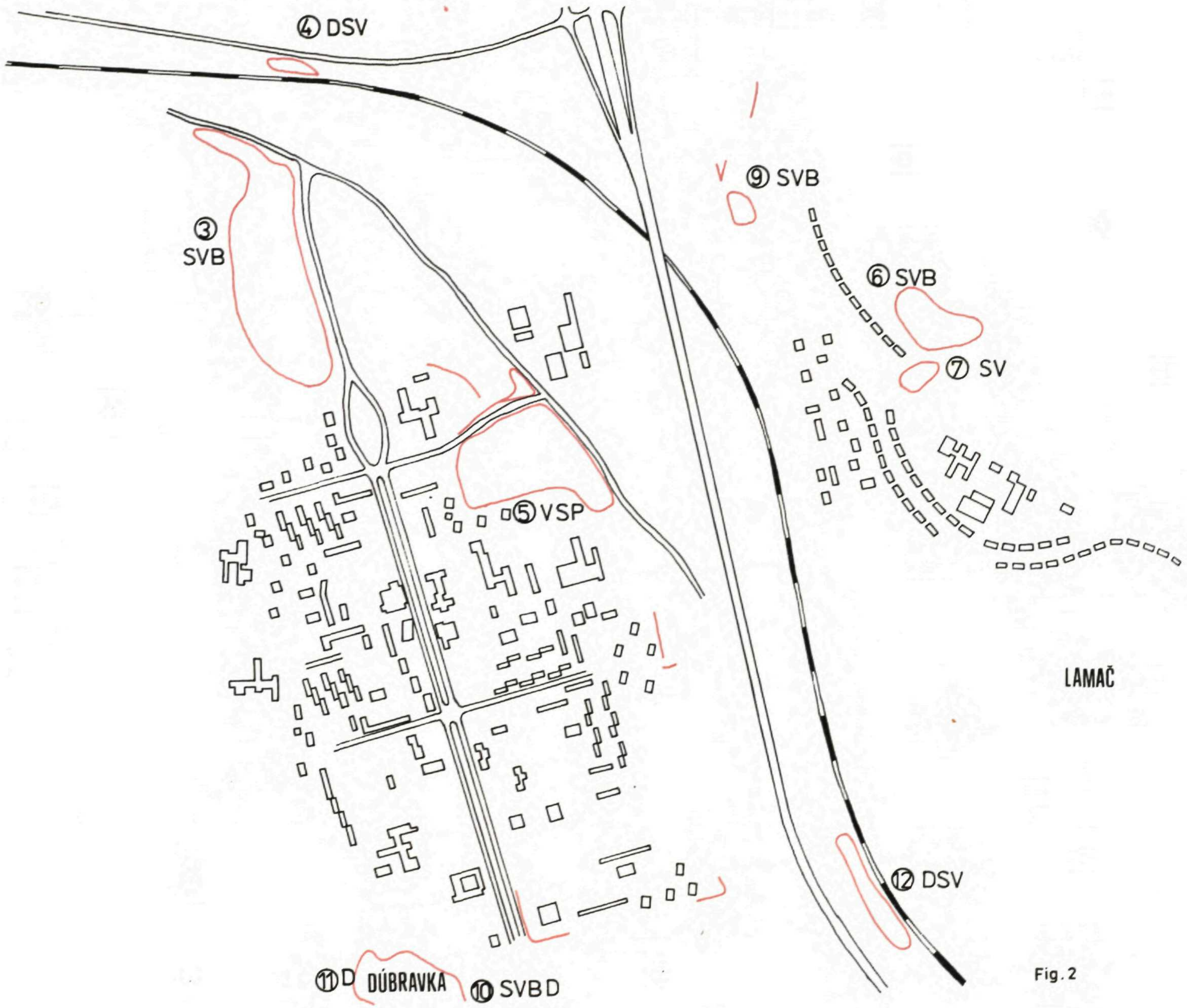


Fig. 2

0 — 0,5 km

EXPLANATION:

- (red outline) the area of the waste deposit
- (red line) the elongated waste deposit
- ⑥ the number of the waste deposit
- SB the composition of the waste deposit:
  - V - the excavation material
  - S - the construction waste
  - B - the large dimension construction waste
  - D - the communal waste
  - P - the industrial waste
  - E -
  - C - the chemical waste
  - T - the toxic waste
  - K - the metal waste
  - X - the waste from the row material excavation

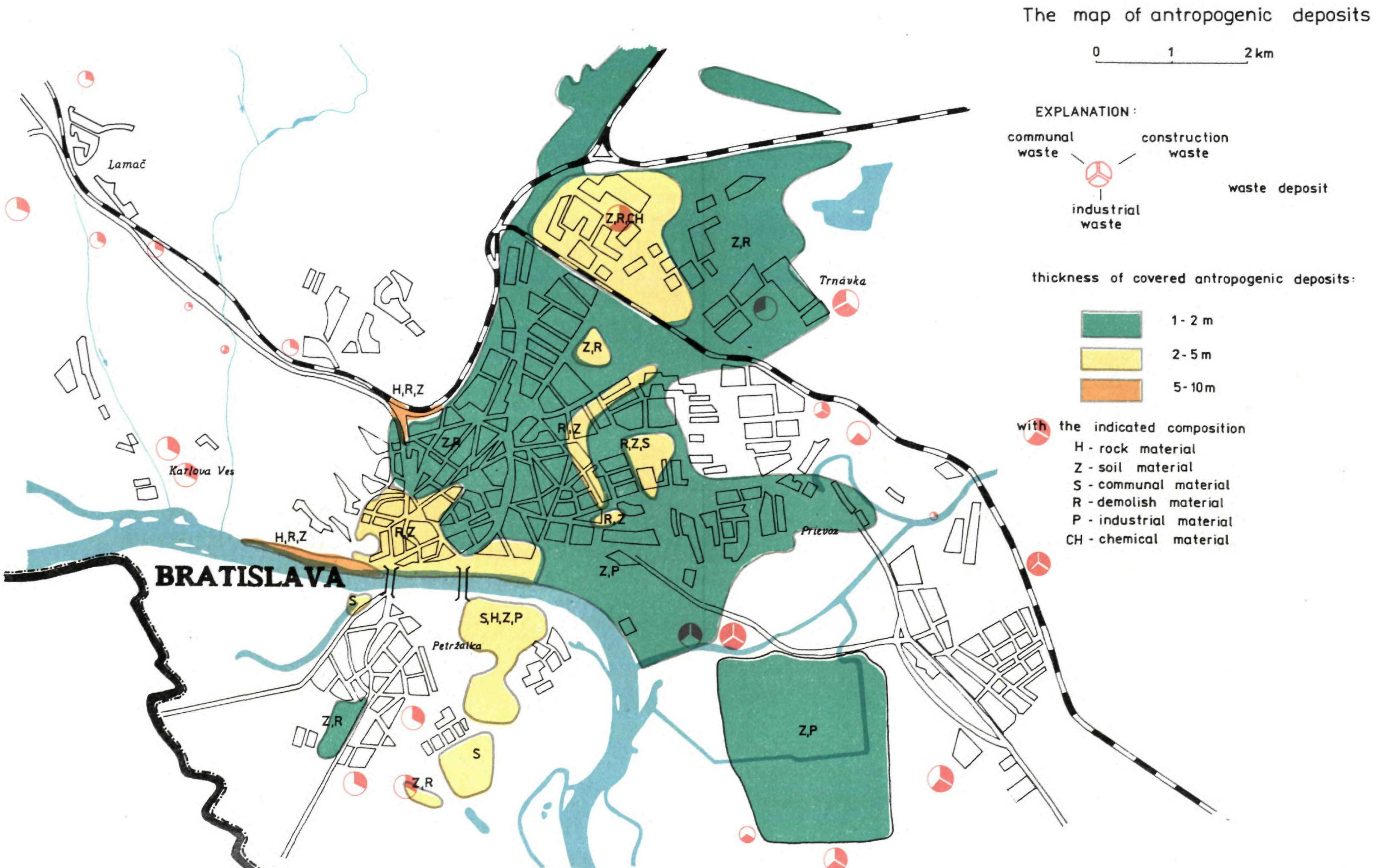


Fig. 4

GÚDŠ EČ 4-1989

anthropogenic material by drilling and depends upon accidentally found "alien" objects or material, like fragments of bricks, glass, wood, concrete, communal wastes a. o.

The experience shows that prevention is the best protection from problems concerning the identification of anthropogenic deposits and accidents of construction as well as the environment devastation. The prevention means a consistent recording of localities of new anthropogenic deposits, description of their characteristic properties, and systematical monitoring of their surroundings.

The problem of searching, deposition and reclamation of anthropogenic deposits is topical in densely inhabited regions like Slovakia. A systematical monitoring of anthropogenic deposits in Slovakia in respect of engineering geology was in 1984—88 initiated at Dionýz Štúr Institute of Geology by compilation of data, including solid waste inventories, data files, maps of the distribution of the anthropogenic deposits, detailed engineering-geological, hydrogeological and hydrochemical investigation of selected waste disposal affecting significantly their surroundings. The work included the evaluation of the experience and a proposal of methodic instructions for the engineering-geological investigation of solid waste disposals of a communal character.

The methods were tested on a model region including the wider vicinity of Bratislava and the Malé Karpaty Mts. (Fig. 1).

Classification and definition of anthropogenic deposits

The term anthropogenic deposits denotes inhomogeneous "materials" resulting from waste products of human activity. They comprise products denotable as the communal waste, displaced rocks and soils due to building works and to terrain changing and a production wastes denotable as industrial waste, displaced materials in consequence of mining, a. o. These anthropogenic deposits were produced in the course of the existence of human society, so they have a variable age, various evolutionary stages and diversified properties as well as effects upon their surroundings.

For the purpose of engineering-geology the anthropogenic deposits should be divided into the following groups:

— wastes
— covered anthropogenic deposits,
— anthropogenic purposive deposits,
— anthropogenic deposits associated with subsurface and surface excavation,
— special anthropogenic deposits.

The wastes are defined as a product of living, productive and building human activities. The wastes have a variable composition and properties and are deposited on a certain place — a disposal which is visually noticeable.

Covered anthropogenic deposits may be characterized as the previous, but they are most frequently revealed by drilling, excavation, building activities,

a. o. Most of them cannot be observed visually. They differ from wastes in some specific properties and their areal extent is usually greater, their age is older, and their engineering-geological properties are more favourable in respect of the consequent utilization of the area.

Purposive anthropogenic deposits were produced by man for a certain practical use. They are causeways, embankments, dams, a. o. denoted as "engineering loads". It is not difficult to identify them in field. We are not interested in them, since their technology is completely managaed by man.

Anthropogenic deposits associated with mining, i. e. products of surficial or subsurficial mining of mineral resources are invented by the respective mining organizations responsible for their state and management. So we are not dealing with them.

Special anthropogenic deposits are represented by burial mounds, cemeteries a. o. Their areal extent and occurrence are small and they are studied by archeologists, historians, a. o. We are only interested in wastes and in covered anthropogenic deposits.

The wastes may be classified from different viewpoints: according to material composition, their shape after deposition, displacement distances, deposition duration, mode of deposition, degree of harmfulness and effects upon the environment, areal extent a. o. Material composition is a characteristic controlling other properties of wastes. The following classification based on the evaluation of the material composition was regarded as optimal during the inventory procedure in the field:

— excavation material
— building waste
— great-size building waste (put-out panels, concrete blocks),
— communal waste
— industrial waste
— energy waste (ash, dross)
— agricultural waste
— chemical waste
— toxic waste
— mining waste.

Single types of wastes may be further specified according to some of their conspicuous properties for example: the excavation material of the soil nature, industrial rubber waste, a. o.

The places of intentional or accidental waste deposition are called disposals. We distinguish organized and non-organized disposals. The organized disposal is a place where the influence of wastes upon the immediate environment is prevented. Others are non-organized or "wild" disposals. The term "organized" is sometimes also applied on disposals admitted by local authorities without engineering-geological and hydrogeological investigations of the basement, basement changing, instructions concerning disposal technology, mode of piling, stratification, interbedding with inert material, sprinkling, fence, supervision, a. o. and reclamation.

Covered anthropogenic deposits

They are characterized — like wastes — as useless products of human activity, covered by buildings and terrain changing. Their areal extent is particularly great in city centres where they have been deposited since the time of commencing settlement. They are always revealed by foundation of construction in city centres. There is a tendency to avoid the foundation of constructions on anthropogenic deposits by the increasing foundation depth on the firm terrain by means of piles. So the presence of anthropogenic deposits complicates building and makes the foundation more expensive. Information about their distribution, composition and thickness will be particularly valuable for planning, projecting and building organizations.

Material composition controlling all other properties of deposits, is the main criterion for the classification of covered anthropogenic deposits for engineering-geological purposes. On the basis of this criterion the covered anthropogenic deposits are divided into:

— rubbish heap material consisting mostly of communal and similar wastes
— rock material composed of desintegrated and displaced rocks
— soil material consisting of displaced, mostly inhomogeneous soils
— industrial material resulting from productive activity
— material resulting from destruction of buildings
— piles comprising all anthropogenic deposits of unknown origin and composition.

As regards age, the covered anthropogenic deposits may be divided into older and younger (present). The World War II is regarded as the turning point between the two age groups. The composition of older anthropogenic deposits is usually monotonous because they consist of destruction material dominant over the rock- and soil material and over the subsidiary rubbish-heap and industrial material. Material composition of older deposits is generally less variable and indicates more favourable engineering-geological properties. The material is usually denser, consolidated and the most part of organic matter is decomposed. The composition of younger anthropogenic deposits is more variable. Processes like rotting, putrefaction, organic matter decomposition usually do not cease, particularly in thicker parts. Heterogeneity of building wastes (concrete blocks, panels, a. o.) causes serious engineering-geological problems in foundation of constructions. The younger anthropogenic deposits can also cause groundwater contamination.

Method of work

First of all it was necessary to form solid waste deposits inventory by means of detailed field mapping followed by engineering-geological investigation of localities selected for a detailed study of the influence of disposals upon environments. The purpose of the study were the creation data files for single registered disposals and their drawing into maps.

Waste disposals inventory

It was necessary to form an inventory sheet for recording comprehensively all data about the waste material and the place of its deposition. The inventory sheet was formed in cooperation with Geofond — an organization concentrating the data about waste disposals, treating the data and rendering information. The inventory sheet represents the basis (input) for the data file concerning waste disposals in Slovakia.

The inventory sheet offers complex basical information about the location and size of the waste disposal, basical data about the waste material, about the environment of its deposition, and data on the inventory and its revision.

A group of data about location:
— inventory number of locality
— administrative district of the waste disposal
— number of the basical topographical map of Slovakia 1 : 10 000 or 1 : 25 000 including the locality
— ordinal number of the waste disposal in the respective map
— topographic coordinates x and y of the waste disposal centre
— locality.

The data are alphanumerical, non-coded.

Data on the size of the waste disposal enable a relatively exact determination of areal extent, thickness and capacity. Recorded are:
— the area of the waste disposal determined by planimeter from a map or by a calculation using simple geometric patterns
— thickness of the waste disposal, determined by the estimation of limit values (from-to). For the capacity estimation the so-called average thickness must be estimated.
— the waste disposal capacity is calculated from the preceding data. With respect to the input values the capacity value is preliminary.

All data of this group are numerical, non-coded. The group of basical data is most extensive. It mostly contains alphanumerical data in coded and non-coded form about the material properties of the waste disposal and its basement, about its influence upon the environment, a. o. as follows:
— the type of the waste disposal (rubbish, building, industrial, combined)
— the character of the waste disposal (organized, "wild")
— legislative state (permitted, non-permitted)
— who made the waste disposal (producer: industrial enterprises, communal sphere, power engineering, civil engineering, agricultural enterprises, inhabitants, unknown producer). The producer is determined after the evaluation of the waste deposit material and of information about the production in the surroundings of the waste disposal

— information about engineering-geological and hydrogeological investigation of the basement, supervision, fencing, mechanization of surface modification, covering by inert material, mode of presumable reclamation
— more exact localization of the waste disposal precising its position in relation to inhabitation, agricultural areas, forests, abandoned excavation areas, rivers and lakes, recreation areas, protected regions, a. o. Data on the waste disposal localization enable the estimation of the eventual negative effects upon groundwater and surface water, recreation areas, inhabitants, a. o.
— the original terrain of the waste disposal — flat, sloping, dissected, with terrain depressions in the surroundings
— the level of the waste disposal in relation to the surroundings — whether the waste disposal surface is on the same level, above the level or below the level of the surrounding terrain or combined. On the basis of this information the optimal mode of reclamation can be selected
— the character of the waste disposal area. It is to be estimated whether the area is filled-up continuously or partly, whether it is along line constructions, a. o.
— the type of deposited material is decisive for the further utilization of the locality. The character of the material controls the intensity of the environment pollution and the possibility of its reclamation for agricultural purposes or its utilization as the foundation soil. The description was based on the classification of deposited material, quoted in the preceding part
— the determination of defects and danger for the environment informs about the pollution of groundwater, surface water, burning or possible self-ignition, putrefaction, the formation of gases, smells, light-material fly, dustiness, the presence of insect and rodents, slope deformations, damage on rare natural localities of flora or geological profiles, damage on cultural monuments, occupation of agricultural soil, a. o. These are significant data on the possible effects of the waste disposal upon the environment. Eventual springs, rivers or lakes close to the waste disposal may be contaminated
— geologic structure of the basement is commonly determined by geological and engineering-geological maps. The data can be obtained by the study of natural and artificial geological exposures
— permeability of the environment is defined by the preliminary value of the hydraulic conductivity coefficient for the entire geological environment in m/s. The environment is either extremely permeable (k_f above 10^{-2} m/s), highly permeable (k_f — 10^{-2}—10^{-4} m/s), medium-permeable (k_f 10^{-4}—10^{-5} m/s), partly permeable (k_f 10^{-5}—10^{-7} m/s), poorly permeable (k_f 10^{-7}—10^{-9} m/s) and impermeable (k_f below 10^{-9} m/s). This is another date significant for the determination of possible groundwater contamination
— groundwater, surface or precipitation water may be present in the form of a continuous groundwater level, in depressions or absent
— possibility of contamination is estimated after the evaluation of the waste material (its age and state), hydrogeological conditions, lithological composition of the basement, a. o.

— the manner of removal is determined on the basis of the preceding information and according to the actual situation. The removal may be done by means of agricultural reclamation, transfer of the material to a more suitable place, burning in incinerators, secondary utilization of material (metal a. o.).

The group of data on registration and revision of information comprises coded alphanumerical data about the authorship and responsibility for the objectiveness of the input data. Recorded are: the name of the person treating the data, the organization for which the data are treated, the data of registration and the name of the reviser. The inventory sheet also comprises a part "Other data" for verbal information that cannot be given in other columns, for example detailed information on material composition, geological profiles, detailed information on lithological composition of the basement, state of investigation, a. o.

Identification of waste disposals

The engineering-geological investigation of waste disposals as anthropogenic deposits was based on the preparatory work:

— the delimitation of the area of interest (Fig. 1),

— compilation of a classification file system and a scheme of data file of waste disposals, the compilation of the inventory sheet and methodical instructions for the uniform waste disposal registration,

— a detailed study of archives records, mainly geological investigation of the region,

— the study of geological conditions mainly occurrences of lithological types of rocks and soils of their physical, mechanical and filtration properties, tectonical conditions is the region, groundwater resources, groundwater- and surface water pollution, industrial structure of the region, its inhabitation, climate, a. o.

In the next stage the field investigation was performed. The direct field observations at localities were recorded in the inventory sheets. The search for the waste disposal localities was partly based on information from local authorities of towns and villages. The information had to be revised, particularly in the cases of illegal or improperly placed waste disposals. We have also tested unproductive areas like swamps, gullies, frequently filled with waste. In larger cities like Bratislava, most attention was paid to industrial zones and housing quarters in the stage of construction with temporary waste accumulations.

We have largely applied photodocumentation for some localities air-photodocumentation from smaller height by means of a special air-plane AN-2 and a common hand-held camera sized to 6 × 6 cm. Photographs were made from 300—700 m above the terrain on black-white panchromatic material and colour slides.

All waste disposals with at least one dimension greater than 10 m were recorded. Smaller waste disposals were only recorded in case of possible contamination of groundwater or surface water.

The waste deposit areas were also marked in topographical maps 1 : 10 000.

Their contours were made by red line and provided with their ordinal number in the maps. Material composition was marked with index symbols (V — excavated material, S — building waste, B — big-sized building waste, D — communal waste, P — industrial waste, E — power-engineering waste, C — chemical, T — toxic, K — metal, X — waste from mineral raw-materials mining).

By the inventory sheet and maps we have obtained detailed information about the waste, the environment of its deposition and consequences of its deposition in the given area and surroundings. For illustration a registration in a map 1 : 10 000 is presented in Fig. 2.

Identification of covered anthropogenic deposits

The beginning works showed that particular procedures were necessary. As for Bratislava, we had to consider the fact that it has been inhabited since ancient times and that most attention must be paid to its historical centre. During the World War II the town was bombed and the ruins were deposited in the town area; the Danube river flowed across the town with meanders and many oxbows are filled-up with the wastes. Bratislava is an industrial centre with extremely variable wastes, deposited — mainly in the past — in the town area or near constructions. Our work based on these basical facts, mostly concentrated upon:

— revision of extensive investigations within engineering-geological and hydrogeological explorations for the town demands focused on the selection of data about the composition and thicknesses of anthropogenic deposits,

— investigations in large industrial plants producing wastes and depositing them in their areas or in the surroundings of the town,

— revaluation of published data about anthropogenic deposits concerning Bratislava,

— the study of historical data, mainly ancient and historical maps as a source of information about excavated areas and ancient Danube channels.

On the grounds of the data on technical works (boreholes, shafts) obtained from Geofond we have compiled the documentation map. The map served as a basis for the estimation of composition and thickness of covered anthropogenic deposits in the area of the town centre of Bratislava.

Engineering-geological maps 1 : 25 000 comprised basical data on anthropogenic deposits ranging to 2 m, 2—5 m and more than 5 m in thickness. The maps were used as an important source of information.

The results of investigation aimed and the mapping of former rubbish-tips, in the town quarter Petržalka in respect of the construction of housing quarters were exact and detailed so the areas could be drawn with a great precision.

The above mentioned oxbows of the Danube r. and the excavated areas of sands and gravels in the Danube alluvial deposits are covered with waste at present. For their identification we have used older topographic maps 1 : 50 000, 1 : 25 000 and 1 : 10 000 and historical maps from the years 1700—1800.

The evaluation of the information obtained resulted in plentiful data for the map of covered anthropogenic deposits in the area of Bratislava.

Conclusions

We have recorded 358 waste disposals in a model region extending on about 2 000 sqkm. Figures 2 and 4 show a part of the region studied — the recorded waste disposals are drawn in the maps 1 : 10 000 and 1 : 50 000.

The registration offers data about waste disposals causing contamination of groundwater, surface water, air polluion a. o. In respect of the extensive devastation of the environment it will be necessary to introduce the regime observations concerning the extent of mainly groundwater contamination and the effects of contamination upon rock environment as a foundation soil. The program will comprise drilling of observation wells permanent sampling of groundwater and soils, hydrochemical research and tests of physical and mechanical properties of soils.

On the grounds of the evaluation of data about covered anthropogenic deposits a relatively detailed map of distribution of covered anthropogenic deposits 1 : 10 000 has been compiled. A part of the map is in Fig. 3.

In the map the following areas are distinguished:

— areas of extremely thick anthropogenic deposits (to 10 m)

— historical centre with anthropogenic deposits 2—6 m thick

— discontinuous, medium-thick areas (2—5 m) of anthropogenic deposits, filling oxbows and excavated areas

— medium-thick areas with exactly determined thickness (given in the map) revealed by a special engineering-geological investigation focused on their localization

— areas of large industrial plants with their own anthropogenic deposits — industrial wastes up to 2 m

— peripheries of the town with anthropogenic deposits 1—15 m thick.

Besides these, the map also comprises unidentified excavated areas and oxbows of the Danube r. with possible occurrence of anthropogenic deposits of unknown composition and thickness.

The data obtained are presented in the Map of distribution of anthropogenic deposits in the area of Bratislava 1 : 50 000 (Fig. 4) with similar content as the maps on scale 1 : 10 000. In the map only three types of areas of anthropogenic deposits were distinguished:

— up to 2 m in thickness

— medium thick areas (2—5 m)

— areas ranging from 5 to 10 m in thickness.