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NATURAL WATER IN SLOVAKIA
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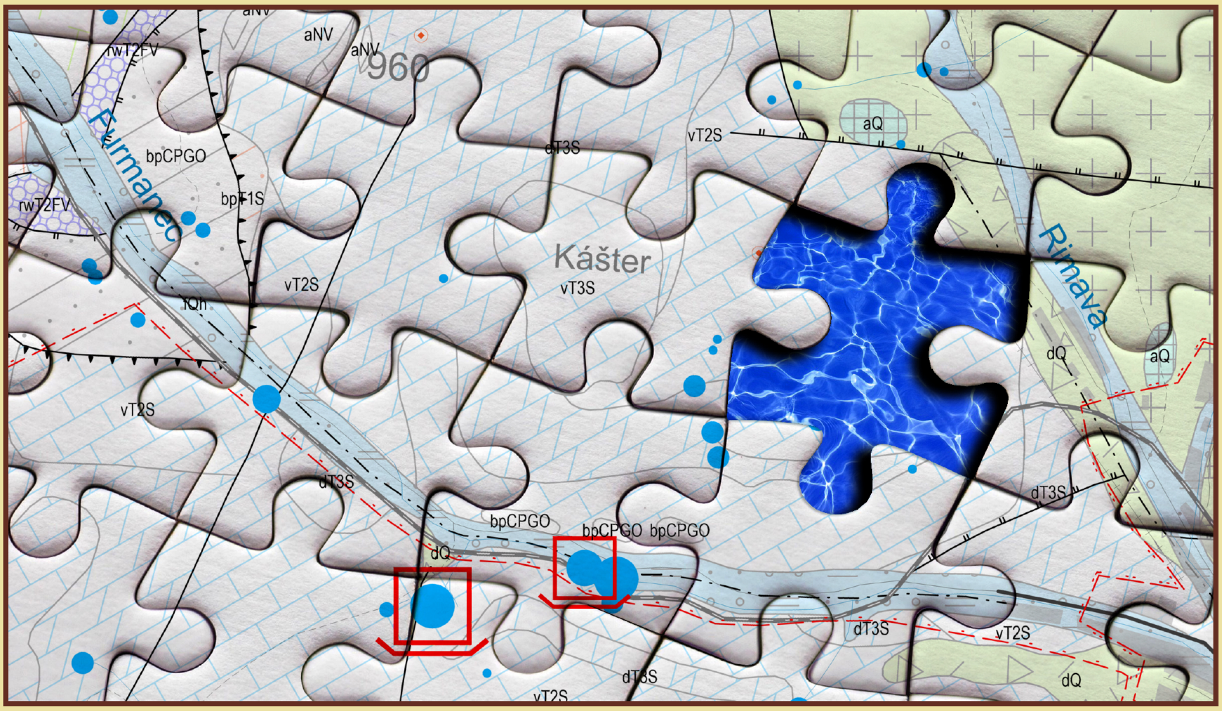

State Geological Institute of Dionýz Štúr, Bratislava

1/2016

SLOVAK GEOLOGICAL MAGAZINE

Periodical journal of the State Geological Institute of Dionýz Štúr is a biyearly presenting the results of investigation and researches in wide range of topics:

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The journal is thematically focused in the issues of the Alpine-Carpathian region.

Bratislava, June 2016

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Preface

Although water is usually considered as life-giving liquid, the real meaning of this frequently used conventional phrase can be understood only by those who are thirsty. Not only human beings, but all living creatures, starting from the smallest bacteria around, up to the birds on the tallest trees in our neighbourhood, all we are water-dependent. Water is needed both as the basic means of metabolism or as the popular wellness facility, depending on the momentary life situation what exactly you live. Those living in the desert know how precious water is, those living on the banks know water that can destroy. Geologists know mountain ranges that were carried away by water. Geologists can also recognize rocks that were born in the water. On our planet, we have to live with the water, and we are living thanks to water. Many times water is missing, but also many times we do not know how to cope with water pouring from the clouds, flooding our fields, breaking our dams. Long droughts and intensive floods, this is something described as temporal variability of water occurrence. Spatial variability of water amounts distribution on planetary surface is even more evident: for how long you should walk from the place you are now to come to the nearest river? Surface waters are extremely distributed both in space and time. Groundwater is different. It is beneath your feet. There are not too many places on the Earth's crust where you can responsibly claim that rock mass you are standing on is lacking any gravitationally driven liquid in its openings. Water masses as slowly moving under the roots of the trees in the park you are walking through. Gently and very, very slowly they are flowing underneath your bed while you are sleeping.

Groundwater, although invisible, is accompanying you on your places. This is what can be also defined as accessibility. You should not walk to the nearest creek to take water, if you were able to dig a well. The question is, how much of water you can take from your well – to supply you and your family or to pump enough for the whole city? Hydrogeologists should know the answer. Unequal distribution of groundwater sources in the country is known for decades, as groundwater was set as the main resource for public water supply and its re-distribution should be secured by kilometres of water pipelines. Hand in hand with intensive drinking water supply infrastructural achievements in 1960s went compilation of the first hydrogeological maps at the Slovak territory showing quantitative aquifer properties. In order to unify different attitudes, standardized methodology set by International Association of Hydrogeologists and UNESCO in 1970 was immediately adopted to cover the area of former Czechoslovakia by a comprehensive edition of hydrogeological maps at a scale of 1:200,000 completed in the period between 1970 and 1978. The story of the next, more detailed edition of hydrogeological maps at a scale of 1:50,000 that started in 1991 can be found within this particular number. General principles of their compilation, displaying mode of their elements, necessary annexes and accessories to these maps, content of explanatory notes and unified data structure to be used in their processing in geographical information systems (GIS) are described here in the first article. The story here continues also by historical overview of compiling these maps in a sequence of editions, showing formats of today's issuing of hydrogeological map on electronic media. All this could be achieved due to the unifying role of the legal document by the Slovak Ministry of Environment – Directive No. 8/2004 – 7 dated on 24th October 2004 "On compilation of basic hydrogeological maps at a scale of 1:50,000", but the irretrievable role of the systematic work of several tens of hydrogeologists in their trial for responsible knowledge of their own country should not remain forgotten.

As groundwater is practically invisible, for decades and centuries there was nothing unusual not to take care about the fate of substances seeping (and disappearing) into the soil. Even today, many of us cannot mentally associate groundwater quality in their dug wells with water quality beneath their latrines standing nearby. Hydrogeochemistry and groundwater quality problems were born under the influence of our growing ability to spread contamination in time and space. Groundwater quantity and groundwater quality should not be treated separately, and in the sense of established groundwater mapping program, double sheet maps – hydrogeological and hydrogeochemical – of the same region should be created. This is due to the Directive No. 9/2004 – 7 dated on 24th October 2004 "On compilation of basic hydrogeochemical maps at a scale of 1:50,000", a matching legal document to hydrogeological maps compilation by the Slovak Ministry of Environment. The second article therefore adjoins the previous one in description of compilation general principles, displaying modes and required accessories to basic hydrogeochemical maps at a scale of 1:50,000. Groundwater quality data handling and their structure in GIS processing is described in order to show the documentation strength of these maps that were constructed on the Slovak territory since 1994.

Reliable documentation of groundwater amounts, quality and aquifer properties represent inevitable condition for proper assessment of hydrogeological settings from the detailed local scales to the generalised country overviews. In the former Czechoslovakia, gathering and storage of relevant information on groundwater started relatively early, with the legal support of Geological Act. Due to this, a state institution of Geofond was created in the 1970's, in charge of collecting manuscript reports from all geological activities in the country. The Geofond, since 1995 incorporated into the State Geological Institute of Dionýz Štúr (SGIDŠ) since that time today maintains a huge archive including some 18,000 manuscript records on hydrogeological surveys. Results of technical activities (mostly drillings) undertaken in terms of groundwater abstraction or monitoring were subsequently stored in a database, today counting records from 25,323 wells and boreholes. Using relatively complex re-interpretation process, their specific capacity data could serve as relatively good source in estimation of approximate values of hydraulic properties of various aquifer types which is described in the third paper here.

If circulating in greater depths, groundwater loses its ability to feed the thirsty, but its ability to become a valuable renewable energy source suddenly appears. Up to date, identified prospective geothermal areas cover 34% of the territory of the Slovak Republic. Although repeatedly reported for basic production and wellbore characteristics, these thermal waters and geothermal resources have never been classified by operation or field thermodynamics. Review on production and field enthalpy distribution, specific exergy and exergy rate capacity of available production and exploration wells is to be found in a specialized paper by SGIDŠ specialists here in this issue. It gives a complex hint on thermodynamic quality of geothermal resources by applying the specific exergy index studies and provides a brief review on operation parameters of sites currently online by definition of utilization and thermal efficiency and performance indexes such as the sustainable index and thermodynamic improvement potential. Such data on Slovak geothermal resources are published for the first time and should encourage all geothermal energy users to further activities.

Contrary to deeply circulating groundwater, surface water – on the Slovak territory mostly water in creeks rivers and reservoirs – is bound to relatively thin zone of interaction. Surprisingly, more than 90% of the chemical composition of surface streams is caused by the interaction of water – rock – gas. Its source is the direct interaction in the bed, and wash-off and inflow of groundwater into a surface stream. A Geochemical Atlas of Surface Water in Slovakia, based on 10,960 samples, enabled an interpretation that was based on a conceptual model of the formation of the chemical composition of the surface water in the Western Carpathians. Based on its end member formation, the surface water could be divided on the basis of five dominant types of lithogeochemical environs in watersheds. These individual earmarked end types were characterized on the basis of statistical methods and thermodynamic modelling. Isotope data were processed here as well, and a comprehensive information is provided within the fifth paper in this issue.

When abstracting minerals, groundwater is always a problem. Mining activities has to cope with seepage into adits or even sudden water breakthroughs to newly opened spaces and maintenance of effective drainage systems. To groundwater quality, mining is always a problem. Rock surfaces that were never exposed to interact with water are rapidly modifying groundwater chemical contents, mostly in unwanted manner. Even decades after their closures, old mine works can negatively affect both surface water and groundwater quality in large scales. Within the last paper in this issue, a regional overview of this phenomenon in the Slovak part of the Western Carpathians is presented. It covers a situation of sudden and significant change after 1990, due to the completion of ore deposits mining. Based on the collection of archive data and new field and laboratory measurements within 14 mining-deposit regions and 71 mining-deposit districts, 1,041sources of mine water are documented here. Still, nearly one half of documented groundwater amounts assumes suitability for drinking water abstraction. The remaining amount with a poor quality represent potential sources of contamination of surface water. Overview of ongoing monitoring shows that persistent contamination of streams due to significant mine water discharges is a real environmental problem in many areas with abandoned mines presence, along with the risk of damage by sudden inrushes of mine water at the surface.

If fire is considered to be a good servant but a bad master, groundwater is more servant, quiet and prepared to be available if we are willing to search. In Slovakia and Central Europe in general, groundwater is generated mostly by snowmelt at the end of winter. We can imagine, that due to its patient slow flow, our grand-granddaughters and grand-grandsons will have to drink the water from the melted snow we were skiing on. Let's hope they will find in in appropriate quality and sufficient quantity: this is a heritage that should never be rejected.

Peter Malík

ACRONYMS AND SYMBOLS

AOX	Adsorbable Organohalogens
CD	Compact Disc
CDPP	Danube Basin Central Depression
COD	Chemical Oxygen Demand
DAO	Data Access Objects
DVD	Digital Versatile Disc
EC	European Council
ES	Extractable Substances
EU	European Union
GeoIS	Geological Information System
GIS	Geographic Information System
GKÚ SR	Institute of Geodesy and Cartography *(Geodetický a geografický ústav Bratislava)*
GPS	Global Positioning System
HG	Hydrogeology, hydrogeologic
HK	Upper Nitra Basin
HTML	Hyper Text Markup Language
IAH	International Association of Hydrogeologists
ID	Identity
IDW	Inverse Distance Weighting
ISH	Individual Space Heating
IWCP	Inner Western Carpathian Paleogene
KD	Komjatice Depression
KK	Košice Basin
LAN	Local Area Network
LeP-SV	Levoča Basin, NE part
LiK	Liptov Basin
LVK	Levice Block
m a.s.l	m above sea level
MD	Mining District
ME	Ministry of Economy
MoE	Ministry of Environment
MR	Mining Region
NES	Non-polar Extractable Substances
NOŠ	New Drainage Gallery *(Nová odvodňovacia štôlňa, Voznica)*
ODBC	Open Database Connectivity
OLE	Object Linking and Embedding
PAH	Polycyclic aromatic hydrocarbons
RV	Required Value
SExI	Specific Exergy Index
SGIDŠ	State Geological Institute of Dionýz Štúr
S-JTSK	Krovak East North *(System of Uniform Trigonometric Cadastral Network)*
SI	Sustainability Index

SQL	Structured Query Language
TDS	Total Dissolved Solids
TOC	Total Organic Carbon
TV	Typical Value
UNESCO	United Nations Educational, Scientific and Cultural Organization
ÚÚG	Central Geological Institute *(Ústřední geologický ústav)*
VBA	Visual Basic for Applications
VDŠ	Voznica Heritage Gallery *(Voznická dedičná štôlňa)*
ViP	Vienna Basin
ZK	Žilina Basin

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1. Slovak Basic Hydrogeological Maps at a Scale of 1:50,000 – Compilation Methodology, Standardised GIS Processing and Contemporary Country Coverage

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Abstract: Methods of basic hydrogeological maps compilation at a scale of 1:50,000 follow the practical experience gathered by compilation of hydrogeological maps at the Slovak territory practically since 1960, most of all by the edition of hydrogeological maps at a scale of 1:200,000 in the period between 1970 and 1978. This experience was enriched by hydrogeological maps compilation at more detailed scale of 1:50,000 applied for several regions on the Slovak territory by State Geological Institute of Dionýz Štúr (SGIDŠ). Legend of these maps was inspired by international experience – IAH/UNESCO standards, classic works and textbooks on hydrogeological cartography by Margat and Struckmeier, hydrogeological maps of the neighbouring countries and especially by hydrogeological map of Albania constructed by Eftimi et al. (1985). Hydrogeological maps constructed according to methodical tool presented here show hydraulic parameters of the rock environment – transmissivity as a primary feature, expressed by colour of polygons. On the same polygon, hatches are used for depicting of geological settings that – especially in the mountainous territories – control boundary conditions for groundwater movement. Selection of linear and point elements respects the details required by applied scale and in the same moment gives a possibility to apply the same methodical tool for compilation of applied hydrogeological maps in more detailed scales.

Keywords: hydrogeological cartography, maps at 1:50,000 scale, aquifer properties, GIS processing, Slovakia

1.1 Introduction

Hydrogeological and hydrogeochemical maps are considered to be the first comprehensive information source about the groundwater, hydraulic properties of rock media and qualitative risks exiting on the soil surface. Based on these maps, it should be possible to realize proper water management measures and landuse planning, taking to consideration groundwater occurrence and groundwater flow. The reader of these maps should be able to propose hydrogeological investigations, and to derive e.g. boundary conditions and aquifer hydraulic conductivity values, as well as qualitative features including qualitative groundwater status and potential risk to which groundwater is exposed.

Going to more detailed scale from 1:1,000,000 through 1:200,000 to 1:50,000 the need of explicit information on each hydrogeological feature is apparent. Basic hydrogeological maps at a scale of 1:50,000 are compiled based on detailed spring documentation, by processing of data from every existing hydrogeological borehole, measured surpluses and loses of discharge amounts to and from surface streams, evaluation of regular regime measurements of discharge and groundwater table on streams, springs and wells and on the inevitable background of good basic geological map in the same or more detailed scale. First maps showing hydrogeological features on the territory of Slovakia were drawn by mapping geologists, mostly to point out the most important springs – sources of potable groundwater, thermal or mineral water. These maps were usually simple schemes depicting surface water bodies together with position of springs and wells. The scale was ranging from general to detail according to the scale of geologically discussed problem. Sometimes hydrogeological features were discussed on the geological background to explain the genesis of groundwater.

Later, with the starting development of hydrogeological science at the end of 1950s and especially in the 1960s, maps were produced to accompany the results of massive regional hydrogeological investigations (Jetel & Kullman, 1970). After that time the whole area of Slovakia, 49,036 km^2 in total, was covered by the uniformly constructed basic hydrogeological maps at a scale of 1:200,000, accompanied by the maps of groundwater chemistry in the same scale (Kullman & Gazda, 1978). 12 map sheets, each ideally covering 7,448 km^2 (98 km × 76 km) were produced in a time of eight years (1970 – 1978) and up to now; this is the only edition of hydrogeological maps that covers the whole Slovakia. Methodology of construction of these maps at a scale of 1:200,000 was adopting the IAH/UNESCO rules published in 1970, and it was unified for all sheets covering the former Czechoslovakia.

The next development step towards more detailed scale of 1:50,000 was connected with primarily the same methodology, later replaced by methodology derived from the set of purpose maps in 1:50,000 by ÚÚG Praha (Krásný 1980; Jetel 1985). In order to create methodology encompassing both the mountainous and lowland settings of Slovakia, hydrogeological maps of neighbouring countries in similar scales had to be compared (for example Anderle & Hansely, 1973; Schubert et al., 2003, Krásný 1979; Krásný et al., 1982; Kadlecová & Teissigová, 2003; Rónai, 1961; Kaszab, 1976; Tóth & Vermes, 1984; Siposs, 1988; Pentelényi & Scharek, 2006; Chowaniec & Witek, 1998; Chowaniec et al., 2015). IAH/UNESCO standards (Anon. 1970), classic works and textbooks of hydrogeological cartography by Margat (1980, 1989) and Struckmeier & Margat (1995), experience with transboundary hydrogeological cartography in the region (Malík et al., 1998) as well as regional masterpiece of hydrogeological cartography by Eftimi et al. (1985) were used in the concept of Slovak hydrogeological maps compilation at 1:50,000 scale. Contemporary method of compilation of basic hydrogeological maps at a scale of 1:50,000 had been gradually developed since 1991. Through the milestones of 1991 (1st methodology; Malík & Jetel, 1991), 1994 (2nd methodology – Malík et al., 1994, published as Malík et al., 2003) and 2004 (Directive No. 8/2004-7 by the Slovak Ministry of Environment) basic principles were accepted, and slightly adopted due to field experience. This type of hydrogeological map shows the background colour according to the average value of transmissivity of the hydrogeological unit, but also respects boundary conditions of hydrogeological units. In the mountainous regions, where transmissivity data is unavailable, this characteristic is replaced by specific groundwater outflow, but these two parameters should be strictly distinguished. The aim of these maps (1:50,000) is to depict the aerial extent and qualitative characteristics of the upper aquifer and the more important deeper ones. The basic characteristics of aquifers – transmissivity and the variability of transmissivity, groundwater outflow, lithology and stratigraphy, are expressed as follows: the mean value of the aquifer transmissivity ($m^2 \cdot s^{-1}$) by background colour, variability of the transmissivity (lateral filtration inhomogeneity) by intensity of colour and the number (index), aquifer lithology by hatching, and aquifer lithostratigraphy by index. The content of basic hydrogeological maps at 1:50,000, gradually covering Slovakia, is now based on field mapping and documentation of hydrogeological features into the background working maps in 1:10,000 in the mountains and 1:25,000 in the lowland territories. The paper in detail describes the principles of hydrogeological maps compilation at a scale of 1:50,000, including applied symbols and appearance of polygons, standardised GIS procedures used to process hydrogeological data to create maps and contemporary country coverage by hydrogeological cartographical outputs at a scale of 1:50,000.

1.2 GENERAL PRINCIPLES OF HYDROGEOLOGICAL MAPS COMPILATION

The purpose of compilation of basic hydrogeological maps at a scale of 1:50,000 was primarily defined by internal methodological documents of the SGIDŠ (Malík & Jetel, 1991; Malík et al., 1994; Malík et al., 2003). Later it was clearly formulated by legal document of the Slovak Ministry of Environment – Directive No. 8/2004-7 dated on 24th October 2004 "On compilation of basic hydrogeological maps at a scale of 1:50,000". According to this, the purpose of compilation of basic hydrogeological maps at this scale is to obtain and evaluate basic information about groundwater and hydrogeological settings, determining groundwater recharge, accumulation and transport in the selected area and also to provide comprehensive information enabling the rational utilization and effective protection of groundwater in land-use planning decisions, remediation, protection and improvement of the environment. The principal content of basic hydrogeological map is in representation of hydrogeological settings of the area, mainly via graphic of rock transmissivity and its spatial change, variability of transmissivity, aquifer boundaries, boundaries of hydrogeological structures (groundwater-bearing systems), aquicludes and aquitards, groundwater dynamics, localization and quantification of springs – natural groundwater outlets and artificial hydrogeological objects. Basic hydrogeological map at a scale of 1:50,000 therefore shows:

Transmissivity (in $m^2 \cdot s^{-1}$) and its variability, lithology and stratigraphy of aquifers and rock environment, and/or mean value of specific groundwater runoff from geological environment in depicted areas (in $l \cdot s^{-1} \cdot km^{-2}$ or mm units; in karstic aquifers, also effective recharge can be shown). These parameters (transmissivity and specific groundwater runoff) are considered to be the basic hydrogeological rock properties. In practice, mean values of specific groundwater runoff are usually displayed in mountainous terrain, respectively in areas where the author considers it impossible to reliably determine transmissivity of displayed rock environment, but also as a complement to the displayed transmissivity. Using specific groundwater runoff as the basic displayed rock property is also suitable in the cases of extremely heterogeneous aquifers with karst-fissure and karst permeability types.

(1) Spatial superposition of several aquifers present in the area. Note: hydrogeological map at a scale of 1:50,000 does not reflect spatial superposition of aquicludes and aquitards.

(2) Water entry into the system (infiltration, recharge), water output from the system (drainage), environments without water exchange between the ground surface and aquifers (zero flow), and human artificial interference with the natural groundwater circulation. Map also shows boundaries of groundwater-bearing systems (aquifers) to express boundary conditions identified – such as flow boundary conditions (*Q = const.*, *Q = 0*, non-constant flow) or potential boundary conditions (*H = const.* or non-constant piezometric level potential) by the use of linear and point elements.

(3) Relations in water – rock system as water inputs and outputs from the system, the occurrence of natural groundwater outlets – springs – and their properties, occurrence artificial hydrogeological objects (boreholes, wells, gauging objects etc…) and their properties, mineral groundwater occurrence, groundwater flow dynamics (flow directions), geological structural and tectonic elements relevant from the hydrogeological point of view, and elements

relevant to groundwater protection and groundwater use by line and point elements.

The main underlay base for compilation of hydrogeological map is a geological map (at a scale of 1: 50,000) and its explanatory notes. Both the knowledge of rock media lithology and lithostratigraphy, hydrogeological information about their permeability parameters.

Basic hydrogeological map tries to express different categories of basic hydrogeological characteristics of aquifers, aquicludes and aquitards by different ways:

a) the mean transmissivity value of rock environment – by different area background colour;
b) the value of transmissivity variability (regional value of areal inhomogeneity of permeability) – by different area colour intensity combined with index value placed within the area;
c) lithology and tectonic character of rock environment – by hatch type and its dip on the map;
d) lithostratigraphical classification of rock environment (name of the geological unit) – by the index value, placed within the area showing relevant rock outcrops;
e) the mean value of specific groundwater runoff – by hatch colour in a given area.

Showing the vertical superposition of several aquifers (displacement of different permeable rocks over each other) is done by window grid. Properties of the uppermost aquifer (hatches, background colour etc.) are shown as the basic in the respective area, while lower aquifer properties are shown in smaller windows organized in a rectangular grid covering the area where the lower aquifer can be found. The depth interval of the lower aquifer can be expressed by window size. It is also possible to express the presence of two underlying aquifers by dividing the window into two parts (if both aquifers are in the same depth interval) or by placement of another smaller window into the previous one if the second and the third underlying aquifers are in different depth intervals. Suitability of showing vertical aquifer superposition depends on the degree of knowledge of these aquifers, on technical reachability of underlying aquifers and on hydrogeological importance of the covered aquifers. It is always on author's decision whether the aquifer vertical superposition is to be shown on the respective part of the map. Also readability of the map should be considered, as too many small areal units ("information windows") can rapidly decrease reader's ability to absorb correct information. It should be also noted, that aquicludes and aquitards are not shown in window grids as these are reserved only for regionally important aquifers.

Colours of line and point elements have a steady conventional meaning according to the relation of water and rock environment, the same as in the principles agreed at IAH / UNESCO international legend for hydrogeological maps (Anon. 1970):

a) green colour: water inputs into the rock environment (infiltration);
b) blue colour: water outputs from the rock environment (drainage);
c) grey colour: no water exchange between the ground surface and the rock environment / aquifer system (zero flow);
d) red colour: artificial interference to the natural groundwater circulation, objects of human impact.

The use of line elements with green, blue and grey colour relates mainly border signs of aquifers to express (where it is sensible and proven) the type of boundary conditions – flow boundary conditions ($Q = const.$ / $Q = 0$, non-constant flow rate) or potential boundary conditions ($H = const.$ or non-constant level of piezometric pressure). Line elements for surface water are kept in blue. Infiltration, drainage or negligible exchange of surface waters with groundwater is expressed by assigning of point markings of appropriate colour. The remaining sections are considered to be unexplored. For other line or point markings which are not related to the input and output of water from the water-rock system, following colours are used:

a) orange colour: used for showing the mineral water features and for the expression of groundwater and surface water chemical composition;
b) violet colour: used for groundwater dynamics elements (flow directions, isolines);
c) black colour: used for geological structural-tectonic features.

Detailed list of basic hydrogeological map elements and illustration modes attributed to various hydrogeological features is given in the following chapter. Please note that there are too many figures to be covered by classical figure captions used in other parts of the text. Their meaning is directly explained on the same place as it is usual in the documents addressing the map compilation legends or methods.

1.3 Displaying Mode Of Elements In Basic Hydrogeological Map And The List Of Markings

1.3.1 Quantitative Aquifer Properties

Mean transmissivity value T [$m^2 \cdot s^{-1}$]

	colour of area			
1		purple RGB: 240-179-255	$T > 3 \cdot 10^{-3}$	($>10^{-2.5}$)
2		blue purple RGB: 183-179-255	$T = 1 \cdot 10^{-3}$ to $3 \cdot 10^{-3}$	($10^{-3} – 10^{-2.5}$)
3		blue RGB: 179-231-255	$T = 3 \cdot 10^{-4}$ to $1 \cdot 10^{-3}$	($10^{-3.5} – 10^{-3}$)
4		teal RGB: 179-255-231	$T = 1 \cdot 10^{-4}$ to $3 \cdot 10^{-4}$	($10^{-4} – 10^{-3.5}$)
5		green RGB: 225-255-179	$T = 3 \cdot 10^{-5}$ to $1 \cdot 10^{-4}$	($10^{-4.5} – 10^{-4}$)
6		orange RGB: 255-236-179	$T = 1 \cdot 10^{-5}$ to $3 \cdot 10^{-5}$	($10^{-5} – 10^{-4.5}$)
7		brown orange RGB: 255-198-179	$T = 1 \cdot 10^{-6}$ to $1 \cdot 10^{-5}$	
8		brown RGB: 209-172-63	$T < 1 \cdot 10^{-6}$	

Maintaining this sequence of colours, the limits of intervals categorising the average values of transmissivity coefficients can be moved. For example, instead of the interval limits $3 \cdot 10^{-5}$ to $1 \cdot 10^{-4}$ ($10^{-4.5} – 10^{-4.0}$) $m^2 \cdot s^{-1}$ the author can set boundaries from $4.0 \cdot 10^{-5}$ to $1.3 \cdot 10^{-4}$ ($10^{-4.4} – 10^{-3.9}$) $m^2 \cdot s^{-1}$ or e.g. from $2.0 \cdot 10^{-5}$ to $4.0 \cdot 10^{-5}$ ($10^{-4.7} – 10^{-4.2}$) $m^2 \cdot s^{-1}$.

To clearly set the mutual linkages between those parts of the hydrogeological map legend that (1) show the mean transmissivity coefficient and (2) show individual rock types and their mean transmissivity coefficient it is recommended to mark each transmissivity interval by number. This number shall be affixed to the left from the box with the corresponding colour section (1). In the part of the hydrogeological map legend presenting individual rock types (2) the relevant numbers are assigned to the rock types, in those cases where the mean transmissivity value was set for them. Also this marking number shall be affixed to the left of the box, providing information about the relevant rock type.

For example:

Relevant part of the map legend showing the scale of the mean values transmissivity coefficient T:

		colour of area	Mean values transmissivity coefficient T [$m^2 \cdot s^{-1}$]
(a)	**3**		$T = 3 \cdot 10^{-4}$ to $1 \cdot 10^{-3}$
(b)	**8**		$T < 1 \cdot 10^{-6}$

Relevant part of the map legend showing rock types:

			lithology, permeability type	hydrogeological function
(a)	3	PG^{BP}	Biely Potok Formation of the Inner Carpathian Palaeogene: grey sandstones *fracture permeability*	aquifer
(b)	8	T^{L}	Upper Triassic dark grey shales (Lunz Member) *fracture permeability*	aquitard

Mean value of specific groundwater runoff q [l·s^{-1}·km^{-2}]

hatch colour:

9	purple RGB: 240-179-255	q > 16 l·s^{-1}·km^{-2} (> 500 mm)
10	blue purple RGB: 183-179-255	q = 13 to 16 l·s^{-1}·km^{-2} (400 – 500 mm)
11	blue RGB: 179-231-255	q = 9 to 13 l·s^{-1}·km^{-2} (300 – 400 mm)
12	teal RGB: 179-255-231	q = 6 to 9 l·s^{-1}·km^{-2} (200 – 300 mm)
13	green RGB: 225-255-179	q = 3 to 6 l·s^{-1}·km^{-2} (100 – 200 mm)
14	brown orange RGB: 255-198-179	q = 1.5 to 3 l·s^{-1}·km^{-2} (50 – 100 mm)
15	brown RGB: 209-172-63	q < 1.5 l·s^{-1}·km^{-2} (< 50 mm)
16	grey RGB: 179-179-179	q undetected or undetectable

The use of specific groundwater runoff mean values as essential displayed characteristic of geological environment is recommended only in exceptional cases where the map author considers it impossible to reliably determine values of transmissivity coefficient. On the other hand, this parameter (specific groundwater runoff) is suitable for delineation of extremely heterogeneous aquifers with karst or karst-fissure permeability types.

Similarly as in the case of mean transmissivity values depiction categories, also for distributing of hatch colours for specific groundwater runoff values the author compiling hydrogeological map can appropriately shift the bounds of category ranges for specific groundwater runoff values. The sequence of colour scale for hatches (grid) according to the above sequence should be still maintained.

Variability of transmissivity coefficient values (regional value of areal aquifer permeability inhomogeneity)

Areal aquifer permeability inhomogeneity is in the basic hydrogeological map expressed by the value of standard deviation of the transmissivity index **Y** (s_Y), or standard deviation of the logarithmic value of specific yield obtained from the borehole pumping tests **q** ($s_{\log q}$), or standard deviation of the logarithmic values of transmissivity **T** ($s_{\log T}$). It is applied in combination with displayed mean transmissivity coefficient values **T** and is expressed together by index (letter) and different intensity of colour used for showing the mean transmissivity coefficient values **T** [m^2·s^{-1}].

	index	colour intensity	s_Y , $s_{\log q}$, $s_{\log T}$
17	a	strong	< 0.3
18	b	strong	0.3 to 0.6
19	c	weak	0.6 to 0.9
20	d	weak	> 0.9
21	n	weak	undetected or undetectable

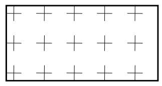
colour intensity

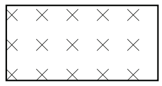
strong	weak
RGB: 240-179-255	RGB: 248-217-255
RGB: 183-179-255	RGB: 219-217-255
RGB: 179-231-255	RGB: 217-243-255
RGB: 179-255-231	RGB: 217-255-244
RGB: 225-255-179	RGB: 240-255-217
RGB: 255-236-179	RGB: 255-246-217
RGB: 255-198-179	RGB: 255-227-217
RGB: 209-172-63	RGB: 209-190-136
RGB: 179-179-179	RGB: 217-217-217

1.3.2 Display of Lithology and Tectonic settings of rock environment

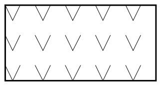
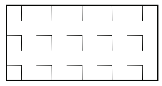
Lithology and tectonic settings of rock environment in basic hydrogeological maps are expressed by various types of hatches (rasters) and their directions (dipping) on the area which is on the map covered by relevant rock type. Lithology of sedimentary rocks is expressed separately for horizontally or sub-horizontally lying sediments (pan structures) and separately for folded and strongly dipping sedimentary layers. The colour of such hatches (rasters) can express the mean value of specific groundwater runoff. If only in grey, transmissivity is used for aquifer characterization instead.

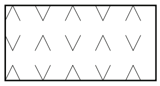
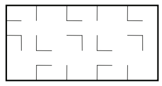
igneous rocks: symbol number:

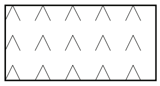
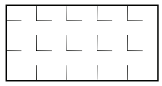
abyssolithic acidic and intermediary igneous rocks  **22**

abyssolithic basic igneous rocks  **23**

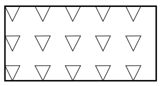
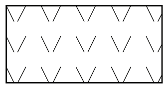
effusives: Tertiary volcanites / Pre-Tertiary volcanites

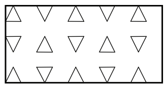
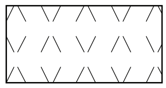
acidic (rhyolites, rhyodacites)  **24**  **25**

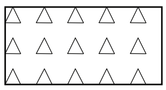
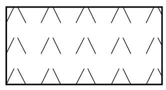
intermediary (dacites, andesites)  **26**  **27**

basic (basalts)  **28**  **29**

volcaniclastics: predominantly coarse (breccias, agglomerates conglomerates ± sands) / predominantly fine (tuffs, sandstones, siltstones, claystones)

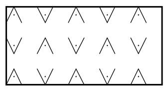
acidic (rhyolites, rhyodacites)  **30**  **31**

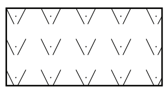
intermediary (dacites, andesites)  **32**  **33**

basic (basalts)  **34**  **35**

Hydrothermal changes of effusive or volcaniclastic rocks (propylitization, argillization) should be in the area, influenced by such a change, shown by point symbol occurring in the hatch of the changed rock.

For example:

(c) propylitic andesites 

(d) argillitic rhyodacitic tuffs 

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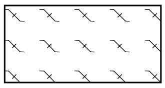
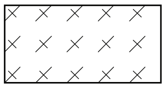
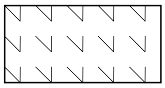
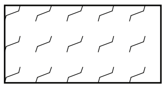
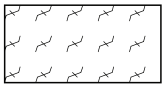
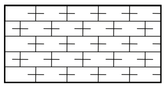
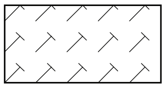
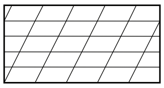
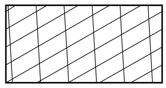
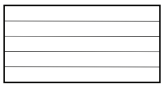
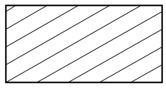
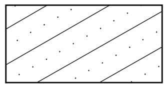
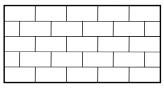
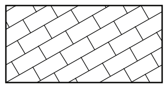
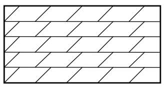
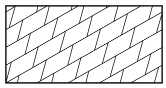
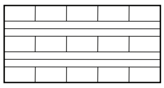
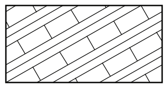
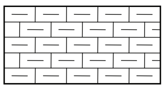
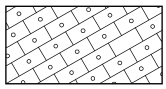
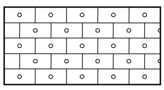
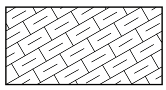
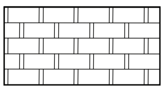
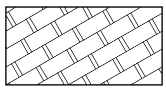
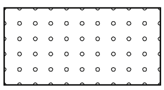
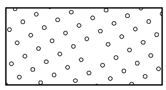
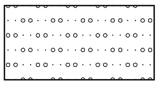
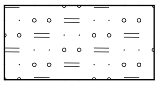
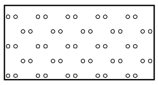
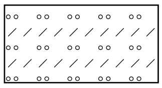
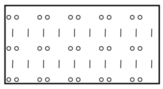
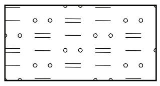
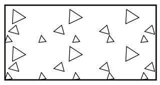
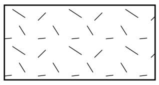
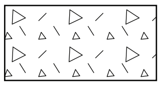
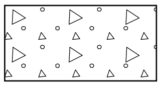
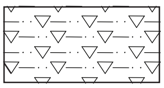
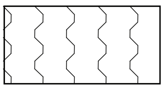
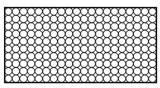
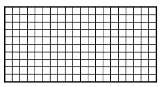
metamorphic rocks:

orthometamorphites (orthogneisses, migmatites)		**36**
metabasites, amphibolites		**37**
metarhyolites, metaandesites		**38**
phyllites, mica schists		**39**
gneisses		**40**
marbles		**41**
quartzites (metagraywackes, metamorphosed arkoses and sandstones)		**42**

sedimentary rocks:	horizontal and subhorizontal				folded or strongly inclined (> 30°)
quartzites		**a**	**43**	**b**	
shales		**a**	**44**	**b**	
interbedded sandstones and shales		**a**	**45**	**b**	
limestones		**a**	**46**	**b**	
dolomites		**a**	**47**	**b**	
interbedded limestones and shales		**a**	**48**	**b**	
variegated limestones (nodular, detritic, crinoidal, sandy)		**a**	**49**	**b**	
marly limestones		**a**	**50**	**b**	
Mesozoic sediments en bloc		**a**	**51**	**b**	
conglomerates		**a**	**52**	**b**	

sandstones	**a**	**53**	**b**
clayey sandstones	**a**	**54**	**b**
interbedded sandstones and claystones	**a**	**55**	**b**
interbedded sandstones and claystones, sandstones predominant	**a**	**56**	**b**
interbedded sandstones and claystones, claystones predominant	**a**	**57**	**b**
claystones	**a**	**58**	**b**
marls	**a**	**59**	**b**
interbedded sandstones and marls	**a**	**60**	**b**
calcareous sandstones	**a**	**61**	**b**
siltstones	**a**	**62**	**b**
clays		**63**	
loams		**64**	
loess and loess loams		**65**	
interbedded sands and clays		**66**	
interbedded sands and clays, clays predominant		**67**	
interbedded sands and clays, sands predominant		**68**	
sands		**69**	
sands covered by flood loams		**70**	
sands covered by loess		**71**	

sandy gravels		**72**
loamy and sandy gravels		**73**
gravels		**74**
gravels covered by flood loams		**75**
gravels covered by loess		**76**
loamy and clayey gravels		**77**
stony debris		**78**
loamy debris		**79**
loamy and stony debris		**80**
glacifluvial sediments		**81**
moraines		**82**
peats and muds		**83**
travertine and calcareous tufa		**84**
anthropogeneous deposits		**85**

1.3.3 STRATIGRAPHY AND LITHOSTRATIGRAPHICAL CLASSIFICATION OF ROCK ENVIRONMENT, ITS HYDROGEOLOGICAL FUNCTION AND PERMEABILITY TYPE

The stratigraphy and lithostratigraphical assignment of each rock environment is expressed by the index containing stratigraphical era / period in its base and lithostratigraphical unit (e.g. formation) in index superscript. The whole index is shown inside the polygon which is on the map covered by relevant rock type. Showing only stratigraphical assignment of rock type without its lithostratigraphical identification is not recommended. Lithological content of rock environment is in the basic hydrogeological map already expressed by hatch and shall not be doubled also in the index.

For example:

(e) PG^{ZL} – Palaeogene, Zlín Member

(f) S^{BP} – Silurian, Bystrý potok Formation

If necessary, povided if it results from geological conditions, it is possible to be more specific about stratigraphic units while maintaining brevity of expression. It is also possible to use instead of lithostratigraphic identification in index superscript the assignment of rocks to relevant tectonic units. Expressing tectonic unit (nappe) identification may not be used until the lithostratigraphic index implicitly indicates this.
For example:

(g) T^{HD}_{CH} – Triassic, "Hauptdolomite"/ main dolomite, Choč nappe

In the case of Quaternary sediments, apart the stratigraphical period (Quaternary) it is useful to indicate also stratigraphical epoch by letter at the end of the index. The first letter should then indicate genetic type of Quaternary deposit (e.g. proluvial, deluvial, fluvial, glacial, glacifluvial or eolian sediments).

For example:

(h) fQp – fluvial sediments of Pleistocene terraces

(i) eQ – Quaternary eolian sediments

All rock environments shown on the map are summarized in the legend on the map margin. Along with explanations of the quantitative characteristics of the rock types (transmissivity by polygon colour, specific groundwater runoff by hatch colour), verbal explanation of rock types' lithostratigraphy, stratigraphy and lithology will be listed together with permeability type and hydrogeological function.

(j) Example of legend summary of rock types shown in the map:

in the map	verbal explanation, permeability type	hydrogeological function
$T2^{KP}$	Middle Triassic grey limestones, Krížna nappe *karstic permeability*	aquifer
T^{L}	Upper Triassic dark grey shales (Lunz Member) *fracture permeability*	aquitard
PG^{BP}	Biely Potok Formation of the Inner Carpathian Palaeogene: grey sandstones *fracture permeability*	aquifer

1.3.4 Display of superposition of several aquifers

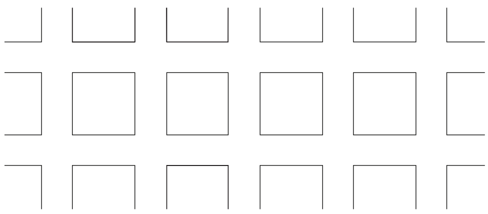
Important aquifers, found at depth under the first uppermost aquifer displayed on the map, are shown by means of inserted grid of windows (apertures). Size of the window depends on the depth to the top of the lower aquifer. In this way it is also possible to show the superposition of several aqui-fers by placing smaller windows inside the bigger ones. When two underlying aquifers are at the same depth range, one window is divided into two horizontal parts. In the window it is possible to show the aquifer characteristics (lithology, stratigraphy, lithostratigraphy, transmissivity value by hatch, index and window colour).

Suitability of showing vertical aquifer superposition depends on the degree of knowledge of these aquifers, on technical reachability of underlying aquifers and on hydrogeological influence of the covered aquifers. It is always on author's decision whether the aquifer vertical superposition is to be shown on the respective part of the map. Superposition of aquifers should be used first of all in the cases where hydrogeological productivity (transmissivity) of underlying aquifer is higher than that of the superimposed one, or where the water quality difference should be the reason.

Aquicludes and aquitards are shown only if present directly on the ground surface, and can be shown in the area between the windows. Aquicludes and aquitards should not appear in the windows. Window grids are reserved only for regionally important aquifers,

The distance of the quadrangle window centres is constant, in basic hydrogeological maps at 1:50,000 scale it is 12 mm, and the size of the quadrangle window side expresses the depth of the upper aquifer boundary (aquifer top) beneath the ground surface, as follows:

86



8 mm: less than 100 m

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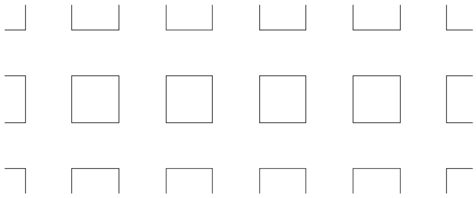
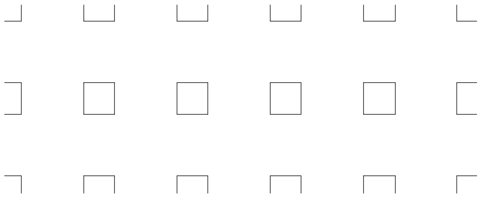
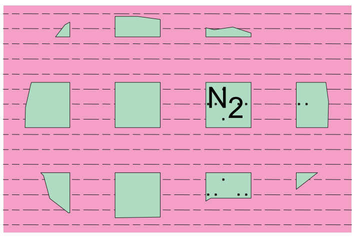
87  6 mm: between 100 to 300 m

88  4 mm: more than 300 m

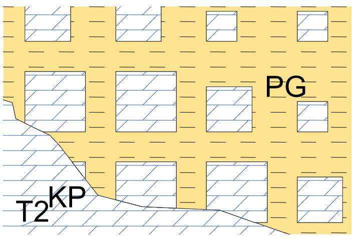
This way of presenting deeper aquifers allows the spatial characteristics of underlying aquifers to be shown (dipping under the overlying confining bed, important uplifted blocks etc.). The next important underlying aquifer is shown in the same window (quadrangle), according to its depth and extent.

Display mode of aquifers' superposition usually optically burdens maps' readability and therefore it is not often easy to decide whether it should be used or preferably not. This also depends on the state of art of geological knowledge in the region. The key role here is played by transmissivity differences in superimposed strata or important changes in water quality with the depth, which are usually considered whether the vertical aquifer superposition should be displayed.

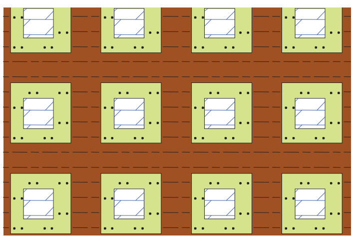
For example:

(k) 

lens of Pliocene sands in the marly clays in depth of 100 – 300 m under the ground surface

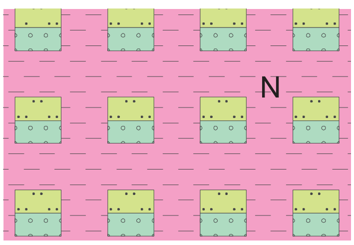
(l) 

gradual dipping of Middle Triassic dolomites under the Eocene claystones

(m) 
two underlying aquifers below the marls and sands at a depth below 100 m and dolomites at a depth of more than 300 m

When two underlying important aquifers occur at the same depth range (e.g. 100 to 300 m), the window will be divided by a horizontal line into two halves. The lower half will be filled by graphical characteristics of the underlying aquifer.

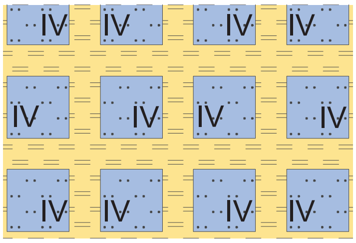
For example:

(n) 

Neogene sands overlie Palaeogene conglomerates (both aquifers) at a depth between 100 and 300 m under the layer of Neogene clays (aquitard)

If within one lithostratigraphical unit important aquifer layers of the identical lithology are repeatedly alternated, they should be shown only in one undivided quadrangle (window, aperture) and the number of aquifer layers in this depth interval will be given by roman number. The colour of the window will be that of the average transmissivity of all the aquifers present within the interval.

For example:

(o) 

alternating of sandy and clay layers in the depth beneath 100 m, number of sandy layers is 4, their total transmissivity is within the interval from $1 \cdot 10^{-4}$ to $3 \cdot 10^{-4}\ m^2 \cdot s^{-1}$

If there are important geological boundaries at depths other than 100 or 300 m it is possible – by author's decision – it is possible to change the depth intervals of usually applied sizes of quadrangle sides (8 mm – 6 mm – 4 mm), e.g. to 200 and 500 m or 50 and 150 what should be then implicitly stated in the map legend.

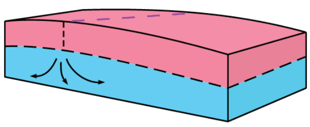
1.3.5 Boundaries of aquifers and aquifer systems

89  thin dark grey — aquifer or aquifer system boundary without defined boundary conditions

90  thin dark grey — boundary of different mean transmissivity value within one aquifer

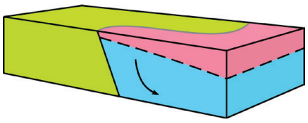
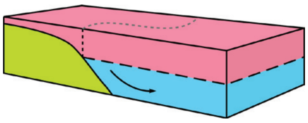
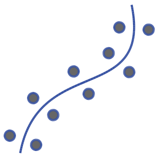
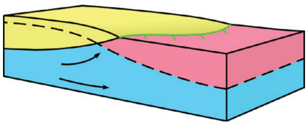
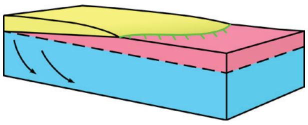
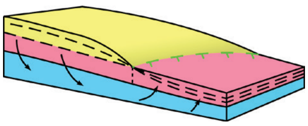
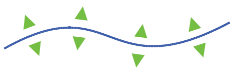
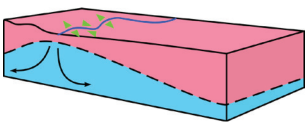
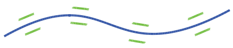
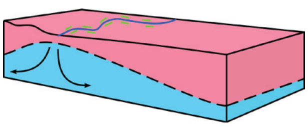
91  thin dark grey — boundary of different value of transmissivity variability within one aquifer

92  purple — orographic (surface) water divide

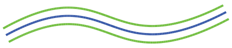
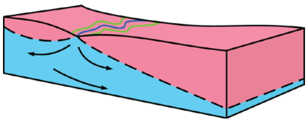
93   purple — groundwater divide

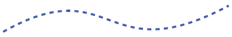
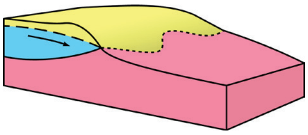
Symbols of boundaries, showing the boundary condition types should be used only where boundary conditions have been clarified and it is appropriate to emphasize them. Selection of the applicable symbols will be left to the author with regard to the applicability on the compiled map.

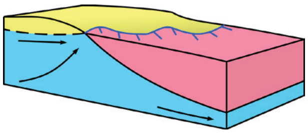
Boundaries with discharge boundary condition:

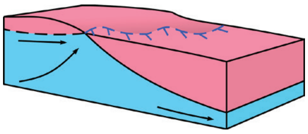
94			dark grey	continuous impermeable boundary (zero discharge)
95			thick dark grey	non-continuous or covered impermeable boundary (zero discharge)
96			blue	negligible water exchange between aquifer and surface stream
97			green	line of transition of confined to unconfined aquifer conditions with groundwater flow direction towards unconfined conditions (recharge of unconfined aquifer)
98			green	aquifer recharge by leaks from semipermeable cover
99			green	boundary between aquifer recharge and ascendant aquifer discharge (line of hydraulic gradient vertical component sign inversion)
100			green blue	verified stable water inputs from surface streams towards groundwater
101			green blue	surface streams, periodically feeding groundwater table

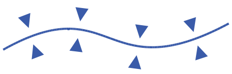
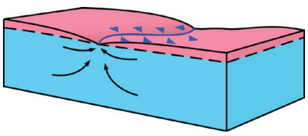
Boundaries with potential boundary condition:

102   green blue — water course or water reservoir embankment acting as an aquifer recharge boundary

103   blue — line of aquifer dewatering on the contact with bottom (seat) aquiclude

104   blue — line of barrier dewatering of an unconfined aquifer

105   blue — line of transition from confined aquifer into unconfined aquifer without occurrence of barrier dewatering (flow direction towards confined aquifer)

106   blue — verified important hidden groundwater surpluses into the surface stream

1.3.6 Natural groundwater outlets – springs

(classified according to average discharge)

107	blue colour	diameter	
< 0.1 $l \cdot s^{-1}$		1 mm	(displayed according to regional circumstances)
0.1 to 1 $l \cdot s^{-1}$		2 mm	
1 to 3 $l \cdot s^{-1}$		3 mm	
3 to 10 $l \cdot s^{-1}$		4 mm	
10 to 30 $l \cdot s^{-1}$		5 mm	

> 30 $l \cdot s^{-1}$		6 mm	
108		blue	line of springs
109		blue	group of springs
110		blue	swallow hole, complete loss of surface stream discharge
111		blue	output of waters after previous sinking

1.3.7 Groundwater dynamics

All symbols: purple colour

112		equipotential lines (piezometric contours) of the uppermost aquifer
113		equipotential lines (piezometric contours) of important deeper aquifer
114		verified groundwater flow direction in the uppermost aquifer (where suitable, the effective groundwater velocity can be numerically expressed in $m \cdot s^{-1}$)
115		supposed groundwater flow direction in the uppermost aquifer
116		verified groundwater flow direction in important deeper aquifer (where suitable, the effective groundwater velocity can be numerically expressed in $m \cdot s^{-1}$)
117		supposed groundwater flow direction in important deeper aquifer

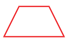
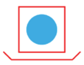
If hydrogeological map shows equipotential lines (piezometric contours) of aquifers, it should be specified which water stage is represented (minimum, maximum, average), or the date for which equipotential lines (piezometric contours) were constructed should be specified. This specification needs to be shown in the map legend and the hydrogeological map itself.

1.3.8 Artificial objects with hydrogeological importance

118		red	existing hydrogeological borehole
119		red	borehole (well) tapped as a water supply
120		red	borehole that provided hydrogeological information, decommissioned

classification of boreholes according to specific yield **q**

q =	< 0.1	0.1 to 1	1 to 10	> 10 ($l \cdot s^{-1} \cdot m^{-1}$)
diameter	2 mm	3 mm	4 mm	5 mm

121		red	important dug well used for water abstraction
122		red	shaft with water pumping
123		red	shaft with water overflow
124		red	important groundwater inlet into underground technical works (mines, tunnels, shafts)
125		red	mine adit with water discharge
126		red blue	groundwater discharge from drainage (meliorations, tube drains, horizontal boreholes)
127		red	important underground technical works (hereditary adit, tunnel) draining significant groundwater amounts or transferring groundwater between watersheds
128		red blue	tapped spring
129		red blue	gauged spring (water quantity)
130		red blue	tapped and gauged spring
131		orange blue	spring with water quality monitoring
132		red blue	gauging station on water course with water stage and discharge gauging
133		orange blue	monitoring of stream water quality
134		red	groundwater level monitoring borehole
135		orange blue	groundwater quality monitoring borehole
136		orange blue	groundwater level and quality monitoring borehole
137		red	artesian borehole

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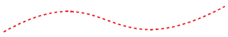
138		red	borehole with groundwater reinjection
139		green	irrigation channel
140		blue	drainage channel
141		red	borehole in cross-section
142		red	mineral ores surficial exploration boundary
143		red	mineral ores subsurface exploration boundary
144		red	rain gauging station
145		red	meteorological station

1.3.9 Groundwater chemical properties, mineral waters

Hydrogeochemical properties of the area are shown on a separate hydrogeochemical map at the same scale of 1:50,000. On the hydrogeological map are therefore shown only the selected hydrogeochemical parameters and the occurrence of mineral waters.

Mineral waters

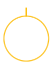
The occurrences of mineral water as springs or groundwater outflow from a borehole are shown by an orange circle around the symbol used for a spring or a borehole. The diameter of the orange circle is always 3 mm more than the diameter of the symbol used for a spring or a borehole.

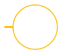
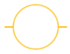
146		orange blue	mineral water spring
147		orange red	borehole, tapping mineral water in the area with already existing natural mineral water outlets
148		orange red	borehole with mineral water from outside the discharge area of existing natural mineral water springs

For example:

(p)			mineral water spring with discharge between 1 and 3 $l \cdot s^{-1}$

Form of orange circle can closely identify:

149		orange	acidulous mineral waters with carbon dioxide (CO_2)

150		orange	sulphate mineral waters
151		orange	chloride mineral waters
152		orange	thermal waters (the diameter of outer orange circle is 3 mm more than the inner one)
153		orange	other mineral waters
154		red orange blue	tapped mineral spring

Protection zones of natural curative sources and natural sources of mineral table waters:

155		red	Ist degree
156		red	IInd degree
157		red	IIIrd degree

Protection zones of drinking water sources:

158		red	groundwater source protection zone of the Ist degree
159		red	groundwater source protection zone of the IInd degree
160		red	groundwater source protection zone of the IIIrd degree
161		light blue	boundaries of the protected water management area

1.3.10 Symbols for geological structure and tectonic elements

Because in the West Carpathians geological structural and tectonic elements play an important role in creating the groundwater circuit and of the existence of anomalous zones of heterogeneous and anisotropic rock masses, the symbols for geological structure and tectonic elements are shown in strong black colour.

162a		fault	a/ verified
162b		-“-	b/ inferred
162c		-“-	c/ covered inferred
	black	(eventual marking the dip orientation of the fault surface)	
163		verified nappe line	
164		inferred nappe line	
165		overthrust fault	

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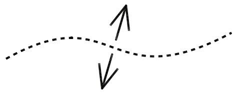
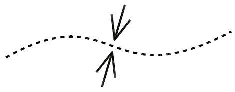
166  axis of anticline

167  axis of syncline

168a 

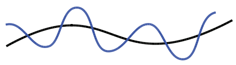
isolines of base: a/ first

168b 

-“- b/ second

168c 

-“- c/ third aquifer

169  zone of intensive tectonic crushing enhancing groundwater circulation

170 brown caves

171 brown karstic abysses / shafts

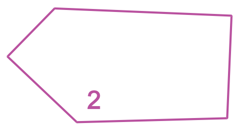
172  brown sinkholes

1.3.11 Topography, cartographic details

The basic topographic layer (villages, towns, roads, railroads, bridges, mountains) are shown in grey. The river system, including annual streams, is in blue. Because each hydrogeological map is accompanied by a cross-section, the line of cross-section has to be shown on the map as well. At the sides of basic hydrogeological map sheet, some larger scales details can be shown in the form of windows, such as for important water-management areas, territories with a complicated geological structures, or structures with promising geological settings from water management point of view. At the common map sheet, also additional explanatory maps can be placed, with parameters selected by the author.

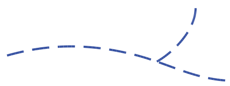
173 

purple cross-section line

174 

purple delineation of details

175  blue water courses (perennial surface streams)

176  blue episodic (ephemeral) water courses

1.3.12 Colour codes used in symbols

Colour:	RGB colour code:		
red (in areas)	255-81-81	orange	115-255-255
blue (in areas)	0-171-255	purple	192-0-255
red (in lines)	255-0-0	brown	155-91-3
blue (in lines)	0-0-255	light blue	129-227-255
green	0-255-0	black	0-0-0
		dark grey	179-179-179

1.4 Accessories to basic hydrogeological maps

1.4.1 Hydrogeological map legend

The legend of basic hydrogeological maps at a scale of 1:50,000 is placed on the same sheet as the map itself. In the legend, all the elements and symbols (polygons, lines and points) shown on the map and cross-section are summarized. Along with explanations of the quantitative characteristics of the rock environment (mean transmissivity value by area background colour, specific groundwater runoff by hatch colour etc...) the rock environment lithology and lithostratigraphy is in the legend also briefly verbally described, together with its permeability type and hydrogeological function as aquifer, aquiclude or aquitard. Inside the boxes of the map legend, also stratigraphical / lithostratigraphical / tectonic unit indexes of relevant rock type should be given.

It has been found in practice of hydrogeological maps construction to be appropriate to clearly set the mutual linkages between the different parts of map legend. To enable better recognition of the mean transmissivity coefficient in individual rock types, each transmissivity interval showing mean transmissivity value should be marked by number affixed to the left from the box with the corresponding colour section. The relevant numbers should be later assigned to the rock types where the mean transmissivity value was set. As in the previous case, also this marking number should be affixed to the left of the "rock type box", providing information about the relevant mean transmissivity value (see the examples given in the methodological part for showing quantitative rock properties).

For point symbols marking springs (natural groundwater outlets) or hydrogeological boreholes, classified by dot size depending on the discharge or specific yield, the dot size distribution is clearly shown in the legend.

1.4.2 Hydrogeological cross-section

On the basic hydrogeological map at a scale of 1:50,000, at least one hydrogeological cross-section is required. The direction of the cross-section should be perpendicular to major hydrogeological structures or geological units shown on the map. The aim of the cross-section is to outline the basic information about the spatial extension of aquifers shown in the map to its user. According to the situation angle line directions can be used, but if possible with minimum of breaks. The length scale of the cross-section is identical with the map scale, but vertical exaggeration can be from two to five times of vertical axis multiplication according to the needs of clearness in structural relations. The exaggeration ratio should be markedly shown by the cross-section. The cross-section should be placed on the same sheet together with basic hydrogeological map.

When displaying the hydraulic characteristics of rock environments in cross-section, vertical change (decrease) of the average transmissivity value should be taken into account. Especially in the case of weathered crystalline rock masses ("hydrogeological massifs") where groundwater flow is concentrated in the near-surface zone, the mean transmissivity value determined from shallow boreholes and displayed on the map using aforementioned principles should be very different in the hydrogeological cross-section. The author should consider showing vertical permeability zonation in hydrogeological cross-section, and if – because of missing data – it is not possible to do that, it must be noted by a text shown next to the cross-section as follows: "Colours of the areas or the hatch colours, expressing the mean transmissivity or the mean specific groundwater runoff are in the hydrogeological cross-section derived from the colours of rock types used for them in the hydrogeological map on the places where they are outcropping. They do not correspond to the actual transmissivity of rocks at greater depths".

1.4.3 Explanatory notes to basic hydrogeological map

Comprehensive explanatory notes should accompany each basic hydrogeological map at a scale of 1:50,000. After an introduction to the region, a brief description of natural settings (geographical, geomorphological, climatological, hydrographical and geological) is given in a recommended comprehensive range of not more than 20 – 30% of the explanatory notes full text. Previous geological, hydrogeological and hydrogeochemical investigations in the area are summarized and briefly evaluated, followed by overview of the used data and the methodology of their processing. A chapter shortly summarizing up-to-date state of groundwater resources evaluation in the region (water management balances, water licencing) follows. The main chapters are devoted to the description of hydrogeological characteristics: hydraulic properties of rock environment, groundwater regime, circulation, prognoses of exploitable groundwater amounts and its qualitative properties. Explanatory notes to basic hydrogeological maps at a scale of 1:50,000 are ended by chapters describing mine waters, mineral and geothermal waters (if applicable).

The binding content of explanatory notes to basic hydrogeological maps at a scale of 1:50,000 for the whole edition should be as follows:

1. Introduction

2. Natural settings

- 2.1. Geomorphological settings, character of the landscape and vegetation in the region
- 2.2. Climatic settings
- 2.3. Hydrological settings
- 2.4. Geological settings
  - 2.4.1. Contemporary state of geological investigations in the region
  - 2.4.2. Geological evolution and characterization of lithostratigraphical units
  - 2.4.2. Geological and tectonic frame of the region

3. Previous hydrogeological and hydrogeochemical investigations

- 3.1. Contemporary state of hydrogeological and hydrogeochemical investigations

3.2. Boundaries of hydrogeological balance units ("rayons") and groundwater bodies in the region

4. **Used data and methodology of their processing**
   4.1. Characteristics of documentary material used for hydrogeological map's compilation
   4.2. Processing methods of hydrogeological data
   4.3. Reproducibility used hydrogeochemical documentation material
5. **Hydrogeological characteristics of the region**
   5.1. Hydrogeological characteristics of rock environment (including characteristics of hydraulic parameters' distribution)
   5.2. Groundwater circulation and groundwater flow regime
6. **Hydrogeochemical settings**
   6.1. Characteristics of processes of groundwater chemical composition genesis in the region
   6.2. Characteristics and classification of groundwater chemical composition
   6.3. Characteristics of groundwater quality parameters in terms of water supply
7. **Data summary on groundwater resources and abstraction**
8. **Mine waters**
9. **Mineral and geothermal waters**
10. **Conclusions**
11. **References**

The name and contents of chapters "8. MINE WATERS" and "9. MINERAL AND GEOTHERMAL WATERS" should be adapted to regional circumstances in accordance with the occurrence of mine waters, mineral water sources and sources of geothermal waters in the region.

Chapter "10. CONCLUSIONS", in addition to a summary of the most important hydrogeological and hydrogeochemical characteristics of the region should also evaluate practical use of acquired knowledge, analyse and synthesize new knowledge gained by hydrogeological and hydrogeochemical investigations carried out in relation to the practical problems of water management and land-use planning. Also relevance of hydrogeological units and groundwater protection zones delineation should be evaluated here, together with presentation of documented new groundwater sources and prospective areas for groundwater abstraction. Valuable information on environmental protection, natural and anthropogenic contaminants, risks posed on groundwater sources quality should also appear in conclusions.

Additional maps showing basic climatic, hydrologic and in particular water management information (e.g. exploitation of groundwater resources, water management balance in the area, "rayons" – hydrogeological balancing units and groundwater bodies) at less detailed scales are conventional parts of explanatory notes to basic hydrogeological maps.

1.4.4 Annexes to the basic hydrogeological map

Basic hydrogeological maps at a scale of 1:50,000 and their explanatory notes are also accompanied by three annexes as processed database files:

1) The list of documented springs – natural groundwater outlets;
2) The list of documented wells and hydrogeological boreholes;
3) Map of hydrogeological documentation.

List of documented springs – natural groundwater outlets consists of two parts, namely (i) a "List of documented springs – natural groundwater outlets with single measurements of discharge and selected physical and chemical parameters"; and (ii) a "List of documented springs – natural groundwater outlets with long-term discharge gauging and/or monitoring of selected physical and chemical parameters".

1a) the list of documented springs – natural groundwater outlets with single measurements of discharge and selected physical and chemical parameters should contain:
- spring coordinates (X and Y, in S-JTSK national coordinate system);
- spring number on the map of hydrogeological documentation;
- sequential spring number on the hydrogeological map (increasing from west to east),
- site name;
- lithology and stratigraphy of the drained rock environment;
- spring type;
- spring altitude;
- discharge (single measurements) in [$l \cdot s^{-1}$];
- outflowing groundwater temperature (single measurement) in [°C];
- air temperature (single measurement) in [°C];
- discharge and temperature measurement date;
- specific electric conductivity of outflowing groundwater (if measured);
- sampling date (if sample was taken);
- brief groundwater characteristics: total dissolved solids, chemical type, components over drinking water standards;
- notes about possible gauging, tapping or water use.

1b) the list of documented springs – natural groundwater outlets with long-term discharge gauging and/or monitoring of selected physical and chemical parameters should contain:
- spring coordinates (X and Y, in S-JTSK national coordinate system);
- spring number on the map of hydrogeological documentation;
- sequential spring number on the hydrogeological map (increasing from west to east),
- site name;
- lithology and stratigraphy of the drained rock environment;

- spring type;
- spring altitude;
- discharge (minimal, average, maximal) in [$l \cdot s^{-1}$];
- outflowing groundwater temperature (minimal, average, maximal) in [°C];
- gauging or monitoring period;
- sampling date (if sample was taken);
- brief groundwater characteristics: total dissolved solids, chemical type, components over drinking water standards;
- specific electric conductivity of outflowing groundwater (if measured);
- notes about possible gauging, tapping or water use.

2) The list of documented wells and hydrogeological boreholes should contain:
- borehole/well coordinates (X and Y, in S-JTSK national coordinate system);
- borehole/well number on the map of hydrogeological documentation;
- sequential borehole/well number on the hydrogeological map (increasing from west to east);
- site name;
- brief geological borehole log;
- depth interval(s) hydraulically tested;
- dates and time of pumping tests;
- altitude of measuring point on the casing;
- depths to the encountered and static groundwater levels in the borehole below the ground surface;
- maximal steadily pumped discharge, in [$l \cdot s^{-1}$];
- relevant drawdown of groundwater level in the borehole, in [m];
- relevant standard specific yield, in [$l \cdot s^{-1} \cdot m^{-1}$];
- total dissolved solids content, in [$mg \cdot l^{-1}$];
- sampling date (if sample was taken);
- groundwater chemical type, components over drinking water standards;
- notes about possible tapping for water supply.

The list of documented wells and hydrogeological boreholes should be supplemented by a table containing gauging results of groundwater levels or piezometric pressures (observation period, long-term maximum, minimum and average in meters a.s.l.) if such boreholes or wells are found in the respective region.

3) Map of hydrogeological documentation

If technically possible, all documented hydrogeological boreholes and springs (natural groundwater outlets) are displayed on the basic hydrogeological map. In many cases it is not practical nor technically possible to view all documentation points (e.g. numerous springs with small discharges in mountainous regions of crystalline rocks). Therefore, these are only shown as points on the map of hydrogeological documentation. The basic hydrogeological map will then show the selected important objects, while in the map of hydrogeological documentation showing of all documentation points (springs and boreholes) is required. In the map of hydrogeological documentation the documentation points, springs or boreholes are distinguished only by symbols attributed to relevant type of hydrogeological objects. The size of the symbol is the same for all hydrogeological objects of the same category (springs or boreholes are not classified according to discharge or specific yield). The diameter of these symbols should be appropriately chosen, to enable the accurate localization of the documentation point on the map and still preserve its visibility.

If technically possible, also the documentation numbers of all the documented hydrogeological boreholes and springs are displayed on the basic hydrogeological map. However, in densely hydrogeologically investigated areas with numerous boreholes, on the basic hydrogeological map only selected boreholes are numbered, but appropriate symbol is shown for all of them. Such areas can then be shown separately in larger scales, with all documented objects labelled, as separate detail windows on the edge of the basic hydrogeological map sheet. On the map of hydrogeological documentation, all hydrogeologically documented objects should be numbered. The author of the hydrogeological maps can also decide which springs (natural groundwater outlets) should be shown on the basic hydrogeological map. Usually, selection of spring documentary points is dependent on features like discharge, water abstraction for water supply, gauging or previous gauging history and water mineral content. On the map of hydrogeological documentation, all documented springs (natural groundwater outlets) should be shown and numbered.

1.5 Submitting of basic hydrogeological maps in GIS outputs

Submitting of basic hydrogeological maps at a scale of 1:50,000 in GIS outputs has unified data structure. Data with point, line and areal (polygon) geometry, as well as textual, are stored in flat files of desktop GIS software (so called tables in MapInfo Pro™ which is used in the SGIDŠ in the process of hydrogeological maps construction). Every file has its precisely defined structure and data requirements, described later. Geographic coordinates of objects are in Křovák projection (datum S-JTSK, north-east). Following is the complete list of individual MapInfo Pro™ tables with detailed description of required data fields. Authors of maps have to keep the defined structure and include all data fields, even unused, but are free to add new fields to the end, based on their needs, as long as the obligatory fields are retained. New fields have to be accompanied with descriptive text.

Areal data (polygons):

unit – hydrogeological units
unit_xsect – hydrogeological units in cross-section
peep – windows (apertures) for displaying aquifer superposition

Linear data:

unit_boundary – boundaries of hydrogeological units
wt_divide – water divides
tect_line – tectonic lines
wspa – protection zones of drinking water sources
wspa_cm – protection zones of natural curative sources and natural sources of mineral table waters
gwt_cont – equipotential lines (piezometric contours)
flow_dir – groundwater flow direction in the uppermost aquifer
xsect_line – cross-sections lines in a map
river – water courses (surface streams, rivers)
unit_boundary_xsect – boundaries of hydrogeological units in cross-sections
tect_line_xsect – tectonic lines in cross-sections

Point data:

spring – *springs (natural groundwater outlets)
bore – *hydrogeological boreholes
objects – hydrogeologically important artificial objects
karst – point karst features

Note:* Besides data on (monitored) springs and (monitored) hydrogeological boreholes required by the Slovak Ministry of Environment Directive No. 8/2004–7, which are submitted as spreadsheet files, additional attributes are included within GIS tables **springs and **bore**, specified later in the text.

Mixed data:

hatch – hydrogeological units hatch patterns
hatch_xsect – hydrogeological units hatch patterns in cross-sections
graphic_xsect – auxiliary graphics (e.g. cross-section bending, water courses, boreholes, vertical scale, etc.) in cross-sections

Textual data:

text_xsect – auxiliary text in cross-sections

Multiple aquifers, multiple cross-sections

In case of multiple cross-sections, each one is drawn into separate table, distinguished by a number in the table name, such as ***tect_line_xsect1**, **tect_line_xsect2***, and so on. When other important aquifers are present underneath the topmost aquifer, tables must also be created for these, named ***unit1**, **unit1_boundary*** and ***hatch1*** (or even ***unit2**, **unit2_boundary*** and ***hatch2***). Furthermore, it is necessary to prepare a table ***peep*** with square windows (apertures) in to top aquifer (***unit***), which structure is defined later in the text.

1.5.1 Structure of individual tables for a hydrogeological map:

Name: ***unit***
Content: hydrogeological units
Topology: closed polygons

Field	Type	Content
HG_INDEX_LOW	Char(10)	hydrogeological index of the unit's lithostratigraphy, lower (e.g. $_{PG}$)
HG_INDEX_UP	Char(10)	hydrogeological index of the unit's lithostratigraphy, upper (e.g. ^{ZL})
DESC	Char(254)	short description of the unit (e.g. fluvial sandy gravel, Holocene)
PERM_TYPE	Integer	permeability type of the unit (1 – fissure, 2 – intergranular, 3 – karst, 4 – karst-fissure, 5 – mixed)
HG_FUNCT	Integer	hydrogeological function of the unit (1 – aquifer, 2 – aquiclude, 3 – regional aquitard, 4 – semipermeable aquitard)
HATCH	Integer	hatch pattern number, in terms of the Directive No. 8/2004-7
FOLD_DIP	Logical	the unit is folded or dipping (TRUE, FALSE)
Q_SPEC	Float	average value of specific groundwater runoff q [$l \cdot s^{-1} \cdot km^{-2}$]
Q_SPEC_CAT	Integer	category of specific groundwater runoff: number 9 to 16 in terms of the Directive No. 8/2004-7
T	Float	average value of the hydrogeological unit's transmissivity coefficient T [$m^2 \cdot s^{-1}$]
T_CAT	Integer	category of transmissivity: class 1 to 8 in terms of the Directive No. 8/2004-7
T_VAR	Float	variability of transmissivity (spatial inhomogeneity of hydrogeological unit's permeability) as e.g. standard deviation of log T values from boreholes ($s_{\log T}$)
T_VAR_ID	Char(1)	variability of transmissivity index: letter a, b, c, d or n in terms of the Directive No. 8/2004-7
N_AQF	Integer	number of aquifers

Name: ***unit_boundary***
Content: boundaries of hydrogeological units
Topology: lines

Field	Type	Content
TYPE	Integer	type of hydrogeological boundary (*1* – boundary of aquifer without boundary conditions defined, *2* – boundary of different mean transmissivity value within one aquifer, *3* – boundary of different value of transmissivity variability within one aquifer)

Name: ***wt_divide***
Content: water divides
Topology: lines

Field	Type	Content
TYPE	Integer	type of water divides (*1* – orographic water divide, *2* – groundwater divide)

Name: ***hatch***
Content: hydrogeological units hatch patterns
Topology: mixed

Field	Type	Content
Q_SPEC_CAT	Integer	category of specific groundwater runoff: number *9* to *16* in terms of the Directive No. 8/2004–7

Name: ***tect_line***
Content: tectonic lines
Topology: lines

Field	Type	Content
TYPE	Integer	type of tectonic lines (*1* – verified fault, *2* – inferred fault, *3* – covered inferred fault, *4* – verified nappe line, *5* – inferred nappe line, *6* – overthrust fault line, *7* – axis of anticline, *8* – axis of syncline)
CIRCUL	Logical	*TRUE* – intensive tectonic crushing enhancing groundwater circulation, *FALSE* – fault without groundwater circulation

Name: ***wspa***
Content: protection zones of drinking water sources
Topology: lines

Field	Type	Content
DEG	Integer	level of protection (*1, 2, 3*), boundary of protected water management area (*4*)

Name: ***wspa_cm***
Content: Protection zone areas of natural curative sources and natural sources of mineral table waters
Topology: lines

Field	Type	Content
DEG	Integer	level of protection (*1, 2, 3*)

Name: ***spring***
Content: springs (natural groundwater outlets)
Topology: points

Field	Type	Content
NUM	Integer	sequential spring number on the hydrogeological map (increasing from west to east)
Q	Float	average spring discharge [$l \cdot s^{-1}$]
SHAPE	Integer	form/shape of a spring (*1* – point, *2* – areal, *3* – linear, *4* –group of springs)
POTAB	Logical	spring is tapped as a water supply (*TRUE, FALSE*)
MONIT_Q	Logical	spring discharge is monitored (*TRUE, FALSE*)
MONIT_WQ	Logical	spring water quality is monitored (*TRUE, FALSE*)
MINER	Logical	mineral water (*TRUE, FALSE*)
CARBON	Logical	carbonized mineral water (acidulous water with CO_2) (*TRUE, FALSE*)
SULPH	Logical	sulphate mineral water (*TRUE, FALSE*)
CHLOR	Logical	chloride mineral water (*TRUE, FALSE*)
THERMAL	Logical	thermal water (*TRUE, FALSE*)

Name: ***bore***
Content: hydrogeological boreholes (wells)
Topology: points

Field	Type	Content
NUM	Integer	sequential number of a borehole on the hydrogeological map (increasing from west to east)
Q_MER	Float	standard specific discharge [$l \cdot s^{-1} \cdot m^{-1}$]
EXIST	Logical	borehole exists (*TRUE – exists, FALSE* – decommissioned)
VODAR	Logical	well is tapped as a water supply (*TRUE, FALSE*)
MONIT_HL	Logical	groundwater level is monitored (*TRUE, FALSE*)
MONIT_KV	Logical	groundwater quality is monitored (*TRUE, FALSE*)
PRELIV	Logical	well overflow (*TRUE, FALSE*)
REINJEKT	Logical	groundwater reinjection borehole (*TRUE, FALSE*)
CHLOR	Logical	chloride mineral water (*TRUE, FALSE*)
THERMAL	Logical	thermal water (*TRUE, FALSE*)
MINER_V	Logical	borehole tapping mineral water in the area with already existing natural mineral water outlets (*TRUE, FALSE*)
MINER_MIMO	Logical	a borehole with mineral water from outside the discharge area of existing natural mineral water springs (*TRUE, FALSE*)

Name: ***objects***
Content: hydrogeologically important artificial objects
Topology: points

Field	Type	Content
NUM	Integer	sequential number of an object on the hydrogeological map (increasing from west to east)
Q	Float	average discharge of an object [$l \cdot s^{-1}$]
TYPE	Integer	object type (*1* – important dug well used for water abstraction, *2* – shaft with water pumping, *3* – shaft with water overflow, *4* – important groundwater inlet into underground technical works (mine, tunnel, adit), *5* – mine adit with water discharge, *6* – discharge from drainage (melioration, tube drain, horizontal borehole), *7* – gauging station on water course with water stage and discharge gauging, 8 – monitoring of stream water quality, *9* – rain gauging station, *10* – meteorological station)
ROT	Float	angle of rotation of the symbol, clockwise (*0* – unrotated) [°]

Name: ***gwt_cont***
Content: groundwater table contours
Topology: lines

Field	Type	Content
AQUIFER	Integer	aquifer level (*1* – uppermost aquifer, *2* – deeper aquifer)
GW_HEAD	Float	(piezometric) groundwater head [m a.s.l.]

Name: ***flow_dir***
Content: groundwater flow directions
Topology: lines

Field	Type	Content
AQUIFER	Integer	aquifer level (*1* – uppermost aquifer, *2* – deeper aquifer)
VER_SUPP	Integer	verification of groundwater flow direction (*1* – verified, *2* – supposed)
GW_VELO	Float	effective groundwater velocity [$m \cdot s^{-1}$]

Name: ***xsect_line***
Content: cross-sections lines on a map
Topology: lines

Field	Type	Content
NUM_START	Char(3)	marking of the cross-section beginning, e.g. 2
NUM_END	Char(3)	marking of the cross-section ending, e.g. 2’

Name: ***river***
Content: water courses (rivers, streams)
Topology: lines

Field	Type	Content
TYPE	Integer	Type of a water course (*1* – permanent / perennial stream, *2* – episodic / ephemeral stream, *3* – dry valley)
INTER	Integer	type of interaction between stream water and groundwater (0 – no interaction, 2 – negligible water exchange between aquifer and surface stream, 3 – verified stable water inputs from surface streams towards groundwater, 4 – streams with periodic feeding of underlain aquifers, 5 – water course or water reservoir embankment acting as an aquifer recharge boundary, 6 – verified important hidden groundwater surpluses into the surface stream)

Name: ***karst***
Content: point karst features
Topology: points

Field	Type	Content
TYPE	Integer	type of karst feature (*1* – cave, *2* – karstic abyss / shaft, *3* – sinkhole, *4* – swallow hole, total stream water loss, *5* – karst spring, exsurgence – water reappearing after previous sinking
ROT	Float	angle of rotation of the symbol, clockwise (*0* – unrotated) [°]

Tables for hydrogeological cross-sections:

Name: ***unit_xsect***
Content: hydrogeological units in cross-section
Topology: closed polygons

Field	Type	Content
HG_INDEX_LOW	Char(10)	hydrogeological index of the unit's lithostratigraphy, lower (e.g. *PG*)
HG_INDEX_UP	Char(10)	hydrogeological index of the unit's lithostratigraphy, upper (e.g. ^{ZL})
HATCH	Integer	hatch pattern number, in terms of the Directive No. 8/2004-7
FOLD_DIP	Logical	the unit is folded or dipping (*TRUE, FALSE*)
Q_SPEC	Float	average value of specific groundwater runoff q [$l \cdot s^{-1} \cdot km^{-2}$]
Q_SPEC_CAT	Integer	category of specific groundwater runoff: number *9* to *16* in terms of the Directive No. 8/2004-7
T	Float	average value of the hydrogeological unit's transmissivity coefficient T [$m^2 \cdot s^{-1}$]
T_CAT	Integer	category of transmissivity: class *1* to *8* in terms of the Directive No. 8/2004-7
T_VAR	Float	variability of transmissivity (spatial inhomogeneity of hydrogeological unit's permeability) as e.g. standard deviation of log T values from boreholes ($s_{log\,T}$)
T_VAR_ID	Char(1)	variability of transmissivity index: letter *a*, *b*, *c*, *d* or *n* in terms of the Directive No. 8/2004-7

Name: ***unit_boundary_xsect***
Content: boundaries of hydrogeological units in cross-sections
Topology: lines

Field	Type	Content
TYPE	Integer	type of hydrogeological boundary (*1* – boundary of aquifer without boundary conditions defined, *2* – boundary of different mean transmissivity value within one aquifer, *3* – boundary of different value of transmissivity variability within one aquifer)

Name: ***tect_line_xsect***
Content: tectonic lines in cross-sections
Topology: lines

Field	Type	Content
TYPE	Integer	type of tectonic lines (*1* – verified fault, *2* – inferred fault, *3* – covered inferred fault, *4* – verified nappe line, *5* – inferred nappe line, *6* – overthrust fault line, *7* – axis of anticline, *8* – axis of syncline)
CIRCUL	Logical	*TRUE* – intensive tectonic crushing enhancing groundwater circulation, *FALSE* – fault without groundwater circulation

Name: ***hatch_xsect***
Content: hydrogeological units hatch patterns in cross-sections
Topology: mixed

Field	Type	Content
Q_SPEC	Float	average value of specific groundwater runoff q [$l \cdot s^{-1} \cdot km^{-2}$]

Name: ***graphic_xsect***
Content: auxiliary graphics (e.g. cross-section bending, river, borehole, vertical scale, etc.)
Topology: mixed

Field	Type	Content
(arbitrary)		

Name: ***text_xsect***
Content: auxiliary text in cross sections
Topology: text

Field	Type	Content
TEXT	Char(254)	complementary text to hydrogeological cross-section (e.g. „HGP-1“, „Cold Creek“, etc.)

Name: ***peep***
Content: windows (apertures) for displaying deeper aquifers
Topology: closed polygons

Field	Type	Content
DEPTH	Float	depth of aquifer below ground [m]

1.6 Basic hydrogeological maps at a scale of 1:50,000 assembled for Slovak territory since 1991

Before 1991, majority of hydrogeological maps at a scale of 1:50,000 was typically compiled as purpose maps attached to final reports of regional hydrogeological investigations and especially regional hydrogeological surveys targeted on estimation of groundwater natural and exploitable resources. Hydrogeological map at this scale were also attached to final reports of regional hydrogeological researches (e.g. Chochol et al., 1984; Kullman et al., 1985; Malík et al., 1986; Malík et al., 1990). In the 1980s however, several attempts of compilation of basic hydrogeological maps at a scale of 1:50,000 with explanatory notes were undertaken. These regions included the northern part of the Košice Basin and Slanské vrchy Mts. (marked by No. 60a on Fig. 1.1; Jetel et al., 1989), Myjavská pahorkatina Hills, Brezovské Karpaty and Čachtické Karpaty Mts. (7 + 8 on Fig. 1.1; Čechová et al., 1990), Chočské and Skorušinské vrchy Mts. (37; Dovina et al. 1990), Nízke Tatry Mts. (42; Hanzel et al., 1990), Hornádska kotlina Basin (50, Jetel et al., 1990), Rimavská kotlina Basin and eastern part of the Cerová vrchovina Hills (47; Zakovič et al., 1989) and the Lučenecká kotlina Basin (41; Škvarka & Bodiš, 1988). In all these aforementioned cases, the primary geological purpose was already the preparation of hydrogeological maps at a scale of 1:50,000. Common principle there was also the way of their compilation by geological regions, in conjunction with previous geological mapping. This means that the map content (depicted territory) was less or more uniform in its principal geological features (closed basins, homogeneous mountain ranges) and the maps were not filling cartographically delineated map sheets. In most of these cases, methodical principles of their compilation were based on the Jetel (1985) methodology, sometimes combined with the principles used in the previous period for compilation of hydrogeological maps at a scale of 1:200,000. Hydrogeological maps, compiled in this “transitional period” were sparsely documented, the reader had to be acquainted only with a brief list of selected springs and hydrogeological boreholes (“the most characteristic for the particular region”) and the explanatory notes referred its user to view only the most prominent hydrogeological features of the region. List of the regions on the Slovak territory, where the first attempts of basic hydrogeological map compilation at 1:50,000 scale were undertaken, is shown in Fig. 1.1.

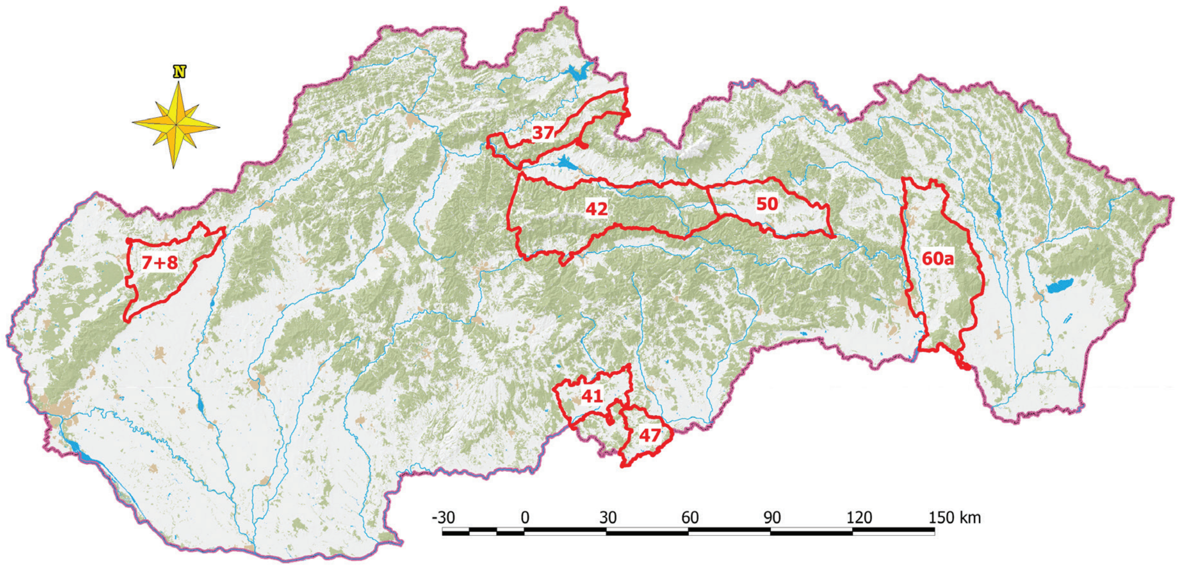


Fig. 1.1 Regions on the Slovak territory, where the first attempts of basic hydrogeological map compilation at 1:50,000 scale were undertaken

According to the newly adopted uniform methodology in 1991 (Malík & Jetel, 1991), in the period of 1991 – 1993 the first uniform set of 11 hydrogeological maps at a scale of 1:50,000 was compiled (Fig. 1.2). It was comprised basic hydrogeological maps of Branisko Mts. (as No. 55 on Fig. 1.2; Malík & Lánczos, 1993), Šarišská vrchovina Highlands (No. 57; Zakovič et al., 1993a), Levočské vrchy Hills (No. 53; Zakovič et al., 1993b), Krivánska Malá Fatra Mts. (No. 23a; Hanzel et al., 1993), Chvojnická pahorkatina Hills (No. 3; Čechová & Kušíková, 1993), Horné Ponitrie region (No. 18; Franko et al., 1993), Zvolenská kotlina Basin (No. 31; Fendeková et al., 1993), Breznianska kotlina Basin (No. 40; Böhm et al., 1993), northern part of the Záhorská nížina Lowland (No. 1a; Čech & Zváč, 1993). At the same time, the regional hydrogeological investigations were completed for the western part of the Biele Karpaty Mts. (No. 11b; Čechová et al., 1993) and Spišská Magura Mts. (No. 49, Jetel et al., 1993), where one of the required outputs accounted for basic hydrogeological map at a scale of 1:50,000 was compiled according to the same methodology. These include also regional hydrogeological investigations for the western part of the Pezinské Karpaty Mts. (Hanzel et al., 1993b). In this particular case, however, the whole territory of the Pezinské Karpaty Mts. was later covered by basic hydrogeological and hydrogeochemical map at a scale of 1:50,000 (Hanzel et al., 1999). Basic hydrogeological maps of this first comprehensive generation of 1:50,000 scaled maps were compiled in cooperation with the Department of Hydrogeology (Department of Groundwater at that time) at Faculty of Natural Sciences, Comenius University in Bratislava. It should be stressed, that for these 11 regions, qualitative equivalents of basic hydrogeological maps – basic hydrogeochemical maps were not compiled, as the methodology for these was still missing. Regional hydrogeochemical settings were only verbally described in explanatory notes. In total, these 11 maps compiled in the 1991 – 1993 period cover the area of 2,889 km^2 (5.9% of the territory of Slovakia, Fig. 1.2).

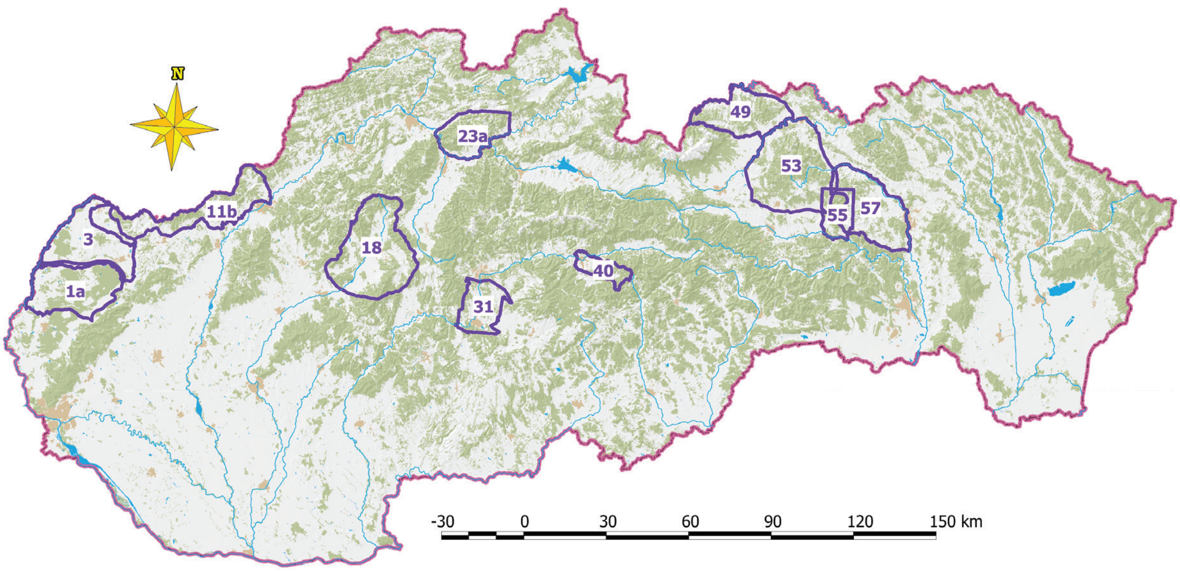


Fig. 1.2 Regions on the Slovak territory, where basic hydrogeological maps (without basic hydrogeochemical maps) at 1:50,000 scale were constructed in the period of 1991 – 1993

The first basic hydrogeological and hydrogeochemical doublesheet maps at a scale of 1:50,000 were compiled during the years of 1994 – 1999. Before that, methodical guidelines on basic hydrogeochemical maps compilation at a scale of 1:50,000 had to be formulated (Rapant & Bodiš, 1994; Rapant & Bodiš, 2003) with small corrections to the hydrogeological maps compilation guidelines (Malík et al., 1994). The following regions of Slovakia were covered by this set of maps: Čierna hora Mts. (No. 59 on Fig. 1.3; Zakovič et al., 1997), Pezinské Karpaty Mts. (No. 2; Hanzel et al., 1999), NE part of the Podunajská nížina Lowland (No. 20a; Malík et al., 1999), the eastern part of the Veľká Fatra Mts. (No. 30a; Malík & Kordík, 1999), the southern part of the Záhorská nížina Lowland (No. 1b; Marcin et al., 1995), Ľubovnianska vrchovina Highlands (No. 54, Jetel, 1999) and the northern part of the Spišsko-gemerské rudohorie Mts. (No. 52a; Scherer et al., 1999). The total land area shown on these maps compiled in the period lasting from 1994 to 1999 was 4,078 km^2, which represents 8.31% of the total area of the Slovak Republic (Malík, 1999). On the occasion of the 29th Congress of International Association of Hydrogeologists which was held in 1999 in Bratislava, this edition of basic hydrogeological maps was presented and briefly described by Malík et al. (1999b).

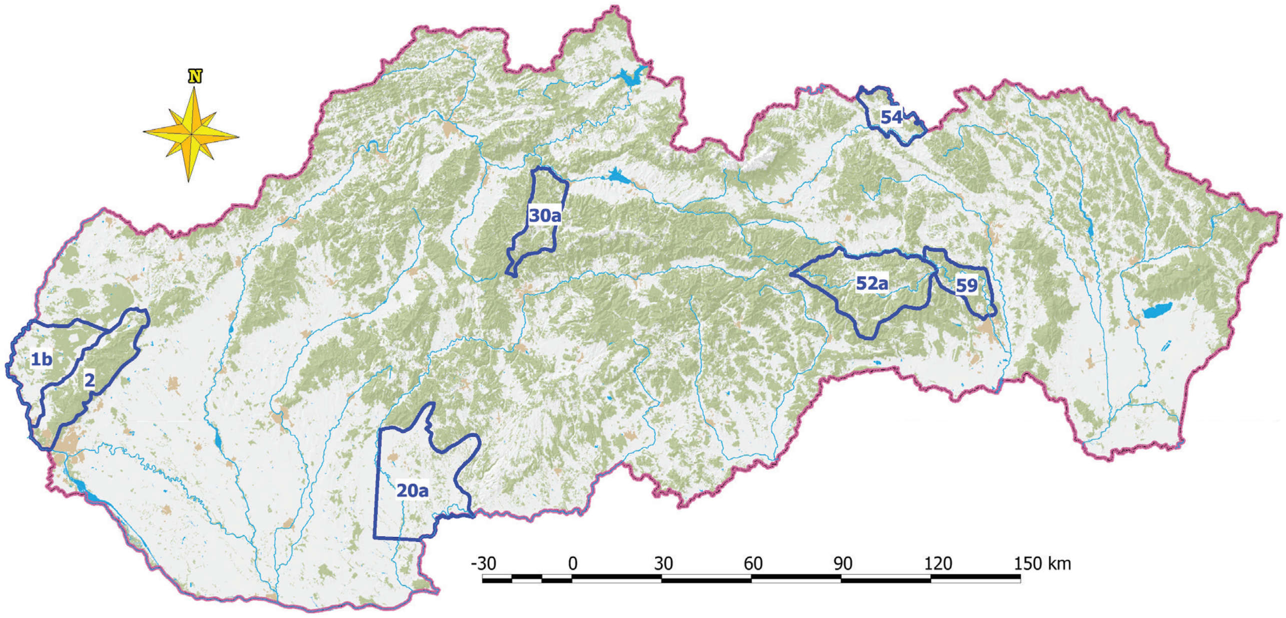


Fig. 1.3 Regions on the Slovak territory, where the first double-sheet basic hydrogeological and hydrogeochemical maps at a scale of 1:50,000 were compiled in the period of 1994 – 1999

Useful details of practical use of the aforementioned principles and methodology of basic hydrogeological maps compilation at a 1:50,000 scale in mountainous region of the Spišsko-gemerské rudohorie Mts. (Scherer et al., 1999) are shown on Fig. 1.4. Here, geological and hydrogeological settings are influenced both by the presence of ancient mine works, karstic features and vertically exaggerated relief where groundwater is drained by numerous springs and mine adits. In the second case (Fig. 1.5), the southern part of the Záhorská nížina Lowland (Marcin et al., 1995) is typical Neogene sedimentary basin where important aquifers are also present below the uppermost one (example of window/aperture method of showing aquifer superposition).

This set of basic hydrogeological and hydrogeochemical maps (1994 – 1999 generation) was also the first set that was gradually transferred into geographical information systems (GIS processing) during its construction. Also publishing process here was converted from paper sheets to electronic formats. Maps were published on CD media in HTML format, and could be viewed by any internet viewer. Moreover, required point information on spring, hydrogeological borehole or hydrogeological unit could be viewed by clicking on the symbol of spring or borehole, or index of hydrogeological unit to open new information window (see also Figs. 1.9 and 1.10 as examples).

In the period from 2002 to 2006, another generation of basic hydrogeological and hydrogeochemical maps at a scale of 1:50,000 followed. These were compiled for 9 regions of Slovakia with a total area of 4,272 km^2 (8.7% of the Slovak Republic; Malík, 2006). These were: Medzibodrožie region (No. 64 in Fig. 1.6; Bajtoš et al., 2004), Vihorlat Mts. (67; Olekšák et al., 2006), Žiar Mts. (No. 21; Černák et al., 2004), Čergov Mts. (No. 59; Marcin et al., 2005), Muránska planina Plateau (No. 47; Švasta et al., 2004), western part of the Veľká Fatra Mts. (No. 31b; Malík et al., 2006), Turčianska kotlina Basin (No. 27; Michalko et al., 2005), Ipeľská kotlina Basin (No. 35, Scherer et al., 2005) and the region of the Podunajská rovina – Žitný ostrov Lowland together with the right bank of the Danube River (No. 4 on Fig. 1.6; Benková et al., 2005).

Example of how hydrogeological settings of a mountainous region with karstic aquifers could be shown on a basic hydrogeological map at a scale of 1:50,000 using aforementioned principles is on Fig. 1.7 (western part of the Veľká Fatra Mts., Malík et al., 2006). Thick gravelly Quaternary aquifer of the Podunajská rovina – Žitný ostrov Lowland (Benková et al., 2005) overlying Upper Pliocene gravels is shown, using window/aperture method on Fig. 1.8.

Later generation of basic hydrogeological and hydrogeochemical maps at 1:50,000 scale for another 10 regions of Slovakia was scheduled for the period 2007 – 2011 and prolonged to 2007 – 2013 (Malík, 2013). Densely documented maps were created for 10 regions of the Slovak Republic (5,323 km^2 what represents 10.9% of the Slovak Republic total surface area). This edition comprised regions of the Žitavská pahorkatina Upland and Pohronský Inovec Mts. (Nos. 15 and 19 on Fig. 1.11; Mikita et al., 2011), Slovenský kras Mts. (No. 51; Malík et al., 2013), Rimavská kotlina Basin (No. 47; Bačová et al., 2012), Bukovské vrchy Mts. (No. 67; Bajtoš et al., 2013), Bánovská kotlina Basin (No. 12; Bahnová et al., 2010), Žiarska kotlina Basin (No. 24; Kováčová et al., 2009), Súľovské vrchy Mts. and Žilinská pahorkatina Upland (No. 22; Marcin et al., 2013), Slovenský raj Mts. (No. 48; Bajtoš et al., 2010), eastern part of the Cerová vrchovina Highlands and Gemerské terasy region (No. 44; Švasta et al., 2013) and the northern part of the Podunajská rovina Lowland (No. 5 on Fig. 1.11; Bottlik et al., 2013). Together with the surface of these regions the state of areal country coverage by basic hydrogeological mapping at a scale of 1:50,000 reached 16,562 km^2 (33.78%) by the end of 2013. However, since the first generation of maps, compiled during the period of 1991 – 1993 was not a "double-sheet" one (for the same territory compiling both hydrogeological and hydrogeochemical map in parallel), the state of country coverage by basic hydrogeochemical maps in

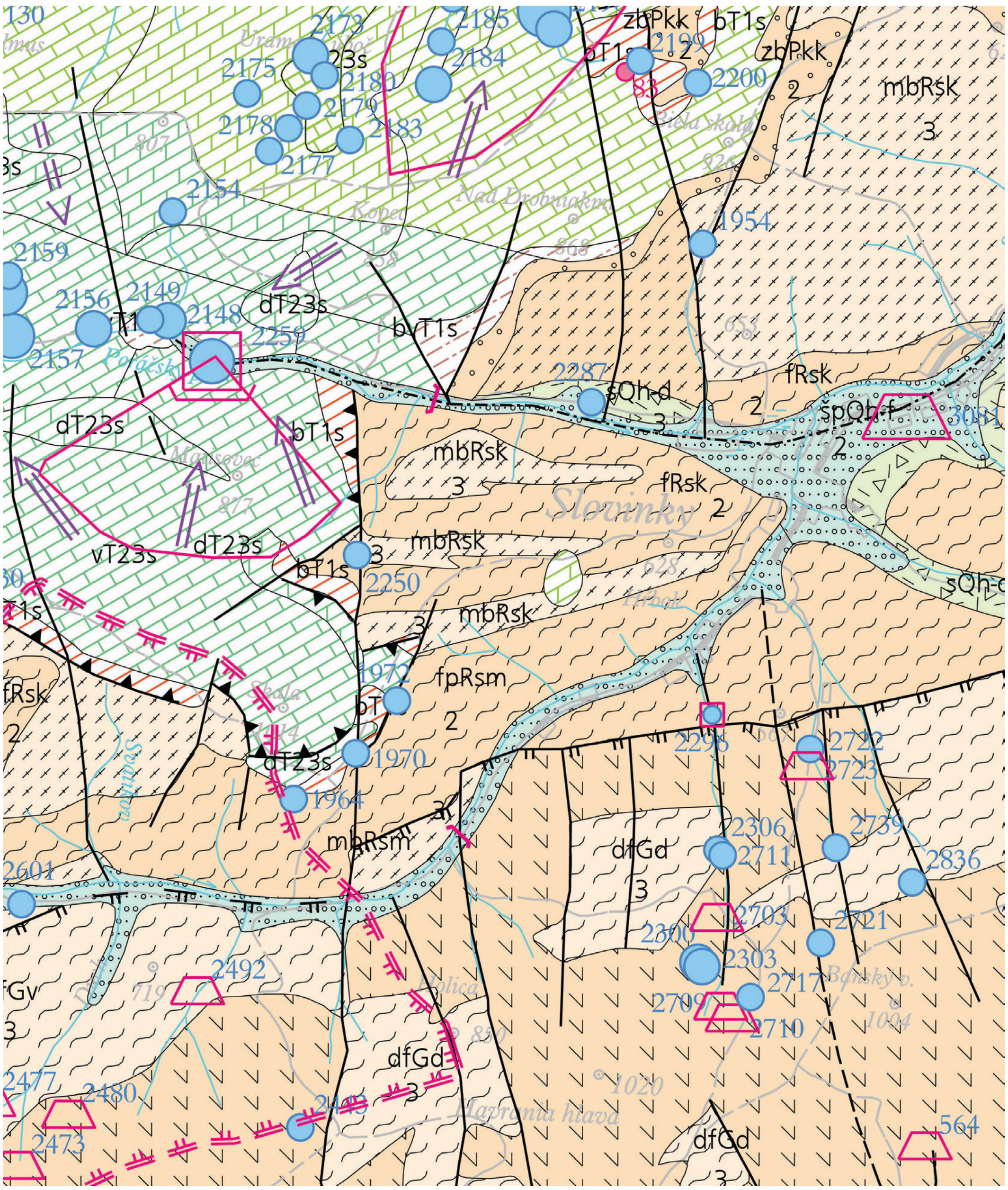


Fig. 1.4 Example of the hydrogeological map of the Spišsko-gemerské rudohorie Mts. at a scale of 1:50,000 (Scherer et al., 1999), mountainous region influenced by the presence of ancient mine works, karstic features and vertically exaggerated relief

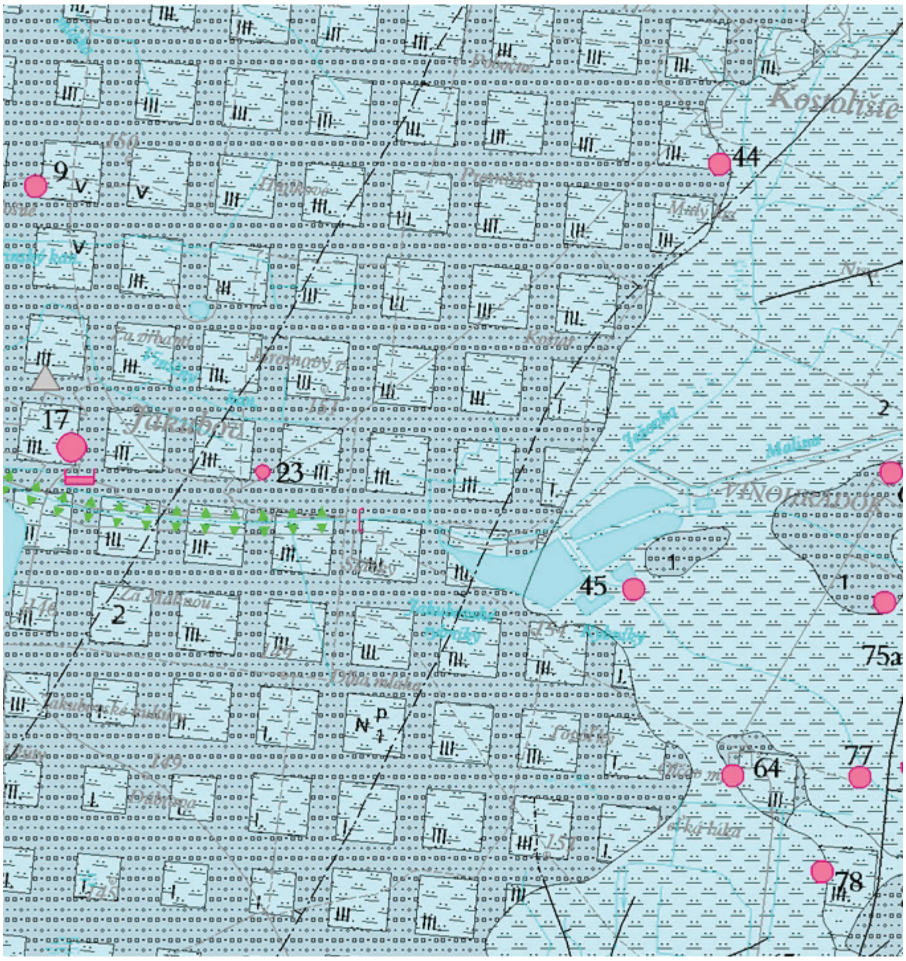


Fig. 1.5 Example of the hydrogeological map of the Záhorská Nížina Lowland at a scale of 1:50,000 (Marcin et al., 1995), Neogene sedimentary basin where important aquifers are present also below the uppermost one

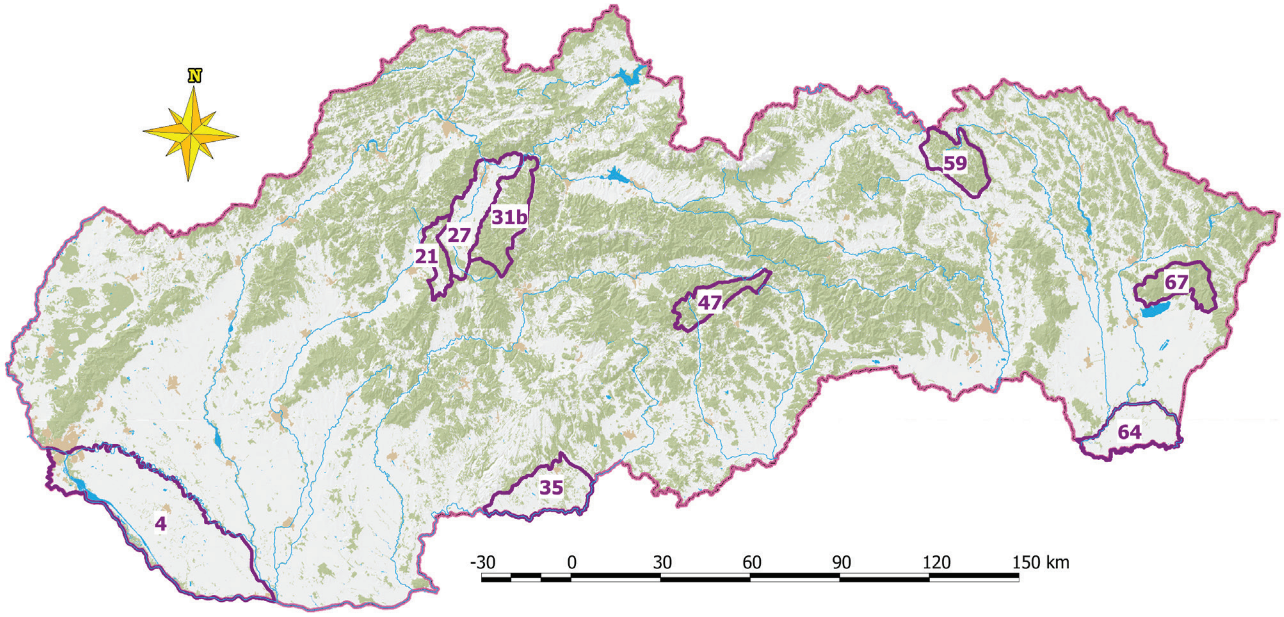


Fig. 1.6 Regions on the Slovak territory, where basic hydrogeological and hydrogeochemical maps at a scale of 1:50,000 were compiled in the period of 2002 – 2006

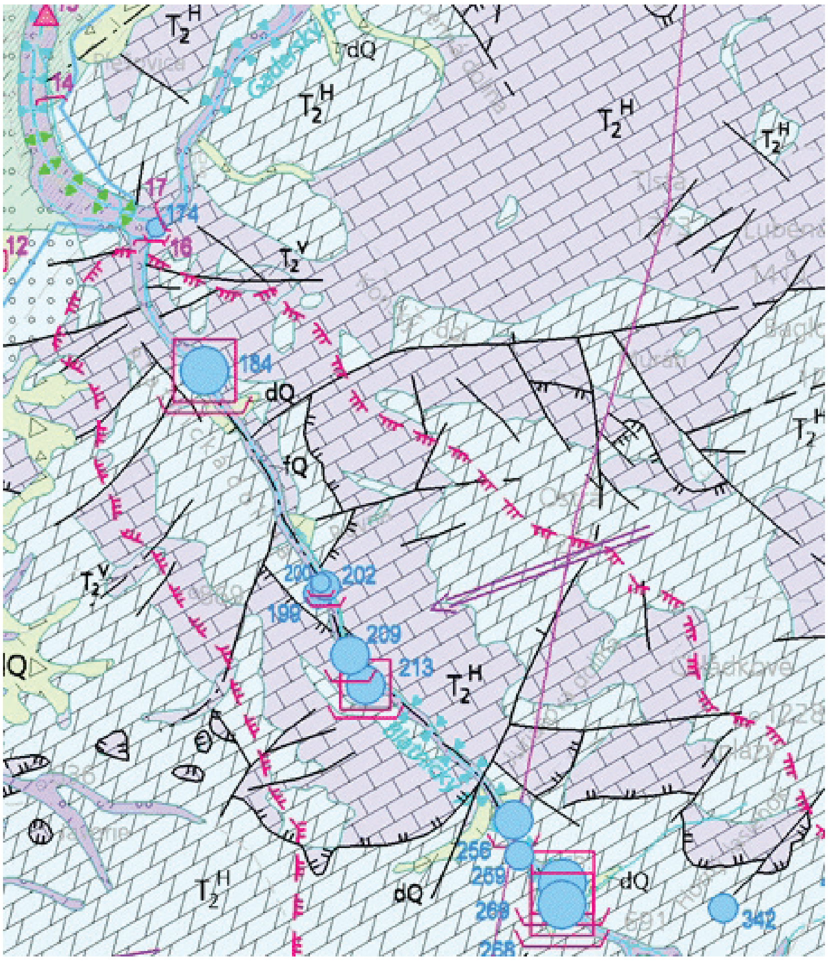


Fig. 1.7 Example of the hydrogeological map of the western part of the Veľká Fatra Mts. at a scale of 1:50,000 (Malík et al., 2006), mountainous region with karstic features in the system of several overthrusting nappes

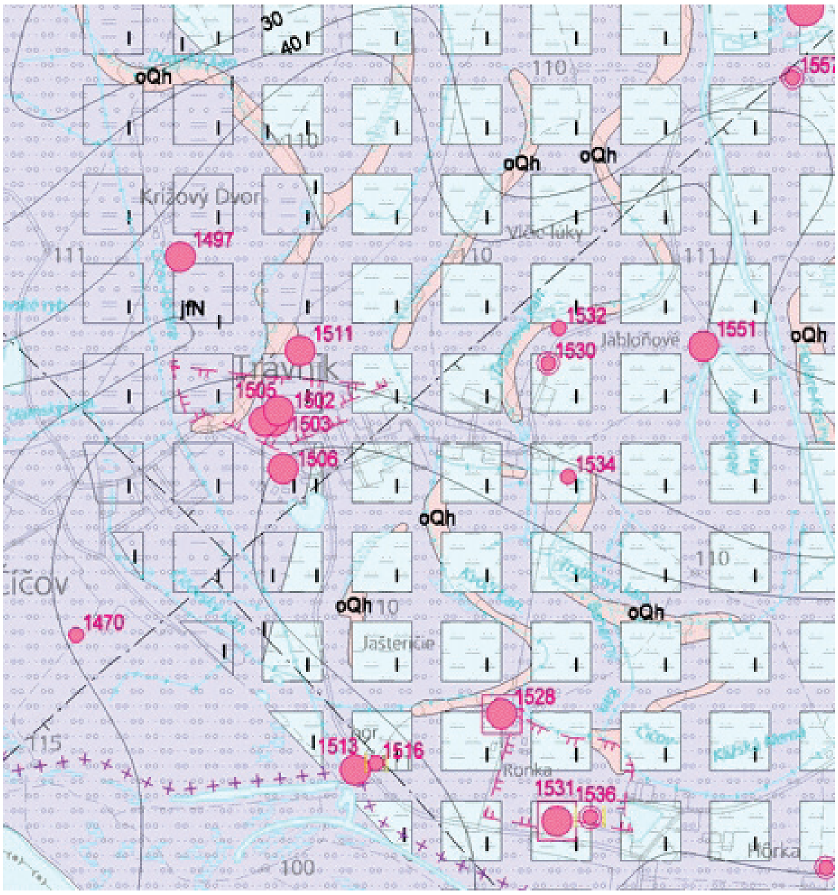


Fig. 1.8 Example of the hydrogeological map of the Podunajská rovina – Žitný ostrov Lowland at a scale of 1:50,000 (Benková et al., 2005), gravelly Quaternary aquifer overlying Upper Pliocene gravels

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Pramene

Číslo prameňa	**27**
Lokalita	**Solka**
Litologický a stratigrafický index	**vT2TŽ**
Nadmorská výška [m]	**385**
Dátum merania Q a Tv	**29.7.2004**
Q - výdatnosť [l / s]	**1,450**
Tv - teplota vody [°C]	**9,0**
EC - merná elektrická vodivosť [µS/cm]	**572**
Dátum odberu vzorky	**7.8.2003**
Mineralizácia [mg / l]	**483,68**
Chemický typ vody	**Ca-(Mg)-HCO3**
Komponenty nad medznou hodnotou štandardov pre pitnú vodu	**NO2**
Poznámka	**Q merané po 100 m, zachytený v betónovej šachte s odtokom, pravdepod. nevyužívaný**

Fig. 1.9 Information window on springs (Žiar Mts., Černák et al., 2004), viewed by clicking on the symbol of spring in electronic version of basic hydrogeological map at a scale of 1:50,000 (feature present in electronically published maps since 1999, in Slovak)

Hydrogeologické vrty

Číslo vrtu v mape	**6**
Označenie vrtu	**B-3**
Lokalita	**Budiš**
Nadmorská výška pažnice [m]	**476,8**
Hĺbka vrtu [m]	**70,00**
Stručný geologický profil vrtu	**0,3 - hlina s organickou prímesou 5,0 - organický sediment 6,5 - piesok hrubozrnný 8,0 - štrk piesčitý 36,0 - pieskovec hrubozrnný 39,5 - piesok 55,0 - pieskovec s preplástkami 57,0 - pieskovec (zlepenec, brekcia, kremenec, kvarcit) 70,0 - piesok**
Filter od-do [m]	**29,5 - 55,2**
Narazená hladina podzemnej vody [m]	
Statická hladina podzemnej vody [m]	**-0,6**
Trvanie čerpacej skúšky [dni]	**29**
Q - čerpané množstvo [l / s]	**2,90 - 2,50**
s - zníženie hladiny vo vrte [m]	**1,46 - 1,18**
q - štandartná merná výdatnosť [l / s / m]	**2,12**
k [m / s]	**1,41E-4**
T [m^2 / s]	**3,62E-3**
Autor	**Klago**
Rok	**1978**
Číslo správy v Geofonde	**41352**

Fig. 1.10 Information window on hydrogeological borehole (Turčianska kotlina Basin, Michalko et al., 2005), viewed by clicking on the symbol of borehole in electronic version of basic hydrogeological map at a scale of 1:50,000 (feature present in electronically published maps since 1999, in Slovak)

the meantime reached only a smaller area of 13,673 km^2 (27.9% of the country territory).

The most important data sources for basic hydrogeological maps compilation are field work together with the past reports about previous hydrogeological surveys on both regional and local levels, stored in the Geofond Archive of the SGIDŠ. According to the geological legislation, valid in the similar wording even several decades ago, reports of every geological prospection should be stored there. Therefore, tens or hundreds of such reports should be studied previous to the compilation of basic hydrogeological map. Data on hydrogeological boreholes are stored in the same archive, and extracting these data from the reports, a huge database on existing hydrogeological boreholes on the Slovak territory, at present containing data on 25,271 boreholes was created and partly interpreted (Malík et al., 2007). In basic hydrogeological map compilation process, these data are processed in detail with regard to regional circumstances. In field work, hydrogeological mapping is performed to the background topographical maps at a scale of 1:10,000 which enable sufficient detail in individual treatment of the documented springs – natural groundwater outlets (Fig. 1.12). Such a detailed mapping is performed especially in mountainous territories of Slovakia. In the cases of uplands or hilly basins, background topographical maps at a scale of 1:25,000 are sufficient as the positon of documented springs is stored by GPS devices since approximately 2005. In lowlands, natural groundwater outlets are rare and mostly borehole database is exploited for hydrogeological map compilation. Discharges of water courses with possible water exchange with surrounding rock environment (surpluses or losses to or from neighbouring aquifers) are measured by the use of current meters especially in mountainous karstic regions.

At present, practically since the beginning of 2014 the process of compilation of the next set of basic hydrogeological and hydrogeochemical maps at a scale of 1:50,000 (six regions with a total area of 2,579 km^2; 5.3% of the Slovak territory) is gradually underway. The set of regions comprises the northern part of the Strážovské vrchy Mts. (No. 16 on Fig. 1.13), Važecký chrbát Mts. region (No. 42a), the Moldava part of the Košice Basin (No. 60b), Trnavská pahorkatina Upland (No. 6), Brezovské Karpaty Mts. (No. 8) and Nitrické vrchy Mts. (No. 16b). Coverage of the territory of Slovakia documented in detail by basic hydrogeological maps after finishing of this edition can be increased to 19,141 km^2 (39.0%).

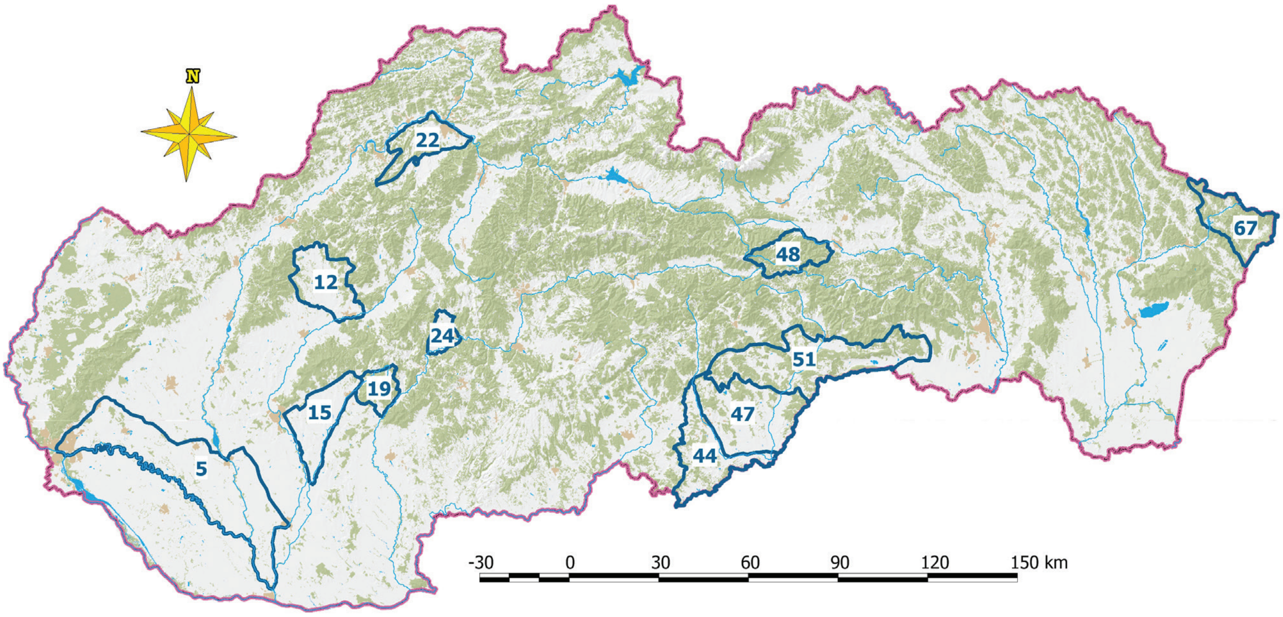

Fig. 1.11 Regions on the Slovak territory, where basic hydrogeological and hydrogeochemical maps in 1:50,000 were compiled in the period of 2007 – 2013

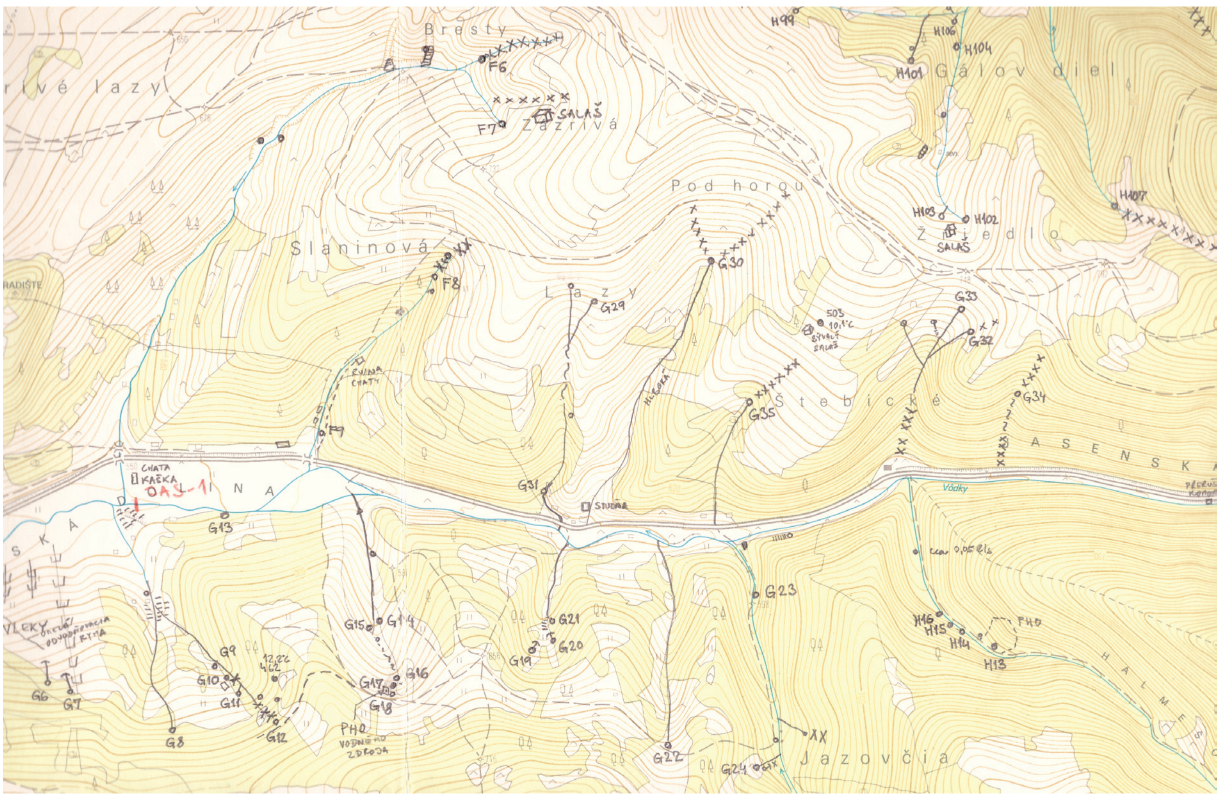

Fig. 1.12 Example of hydrogeological mapping to background topographical maps at a scale of 1:10,000 for proper springs' documentation.

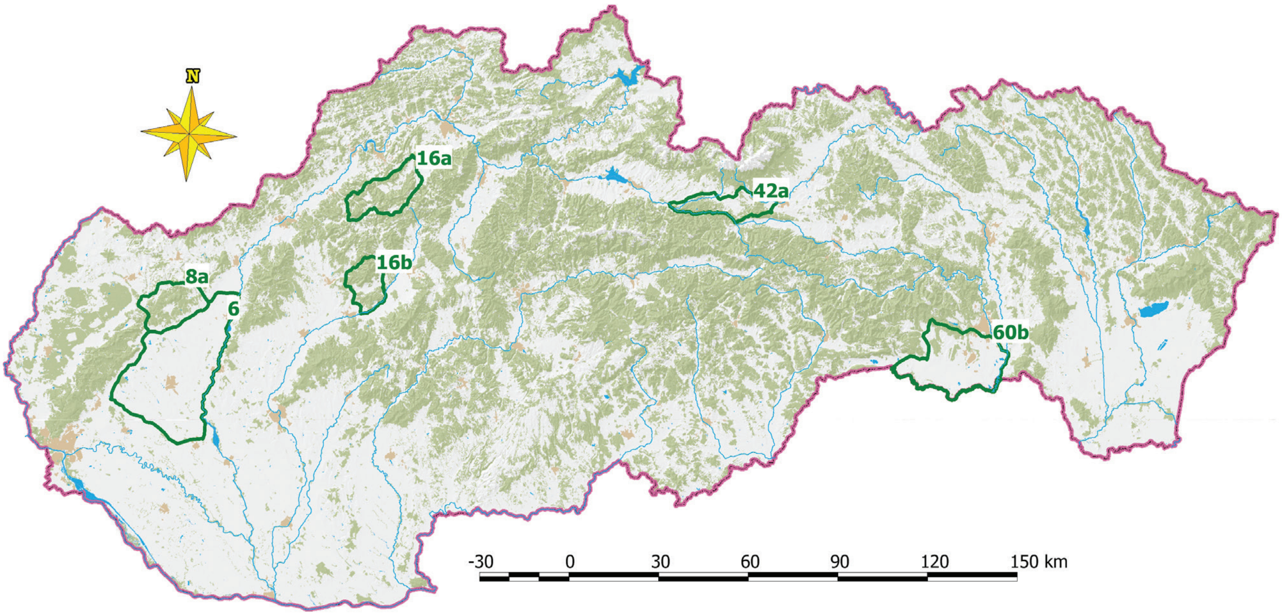

Fig. 1.13 Regions on the Slovak territory, where basic hydrogeological and hydrogeochemical maps in 1:50,000 are being constructed at present (since 2014)

1.7 Concluding remarks

Basic hydrogeological and hydrogeochemical maps can be considered as sources of initial background information on hydrogeological settings of the territory, suitable for providing the first evaluation of activities which can affect or potentially affect groundwater quantity or quality in the area, in particular abstracted sources for drinking water supply. Based on informations contained here, serious water management measures and land-use planning decisions can also be done, as these can take into account the presence of important groundwater resources as well as groundwater flow. Hydrogeological maps can act as the first-brainer in hydrogeological surveys design, or for boundary conditions and aquifer hydraulic properties inputs to groundwater flow and transport models, or as the first simple tool in groundwater contamination assessment or pollution threats to existing groundwater resources, respectively. Presented basic hydrogeological maps at 1:50,000 scale are compiled based on very detailed hydrogeological documentation sources – hundreds of springs and hydrogeological boreholes, measurements of groundwater surpluses to water courses, evaluation of springs' discharge regime, surface streams flow analyses and monitoring of groundwater levels in wells in conjunction with the basic geological map. The first presentations of hydrogeological information on maps correlate in time with the initial development of hydrogeology as a separate geological discipline. On the Slovak territory, the level of shown detail gradually softened from general scale maps at 1:1,000,000 to the practical regional scale at 1:50,000. Currently, hydrogeological maps at 1: 50,000 compiled by hydrogeologists of the SGIDŠ are becoming fundamental geographic information systems with corresponding detail of its scale.

Fig. 1.14 CD/DVD media containing basic hydrogeological maps at a scale of 1:50,000 in simple HTML format enabling also viewing of relevant point information on springs, boreholes or water analyses. These are attached to classically printed explanatory notes.

In 2013, SGIDŠ decided to start with the edition of explanatory notes to the basic hydrogeological and hydrogeochemical maps at a scale of 1:50,000 series in the form of classic textbooks, with uniform content as defined in the Directive No. 8/2004-7 by the Slovak Ministry of Environment. The original idea to publish hydrogeological and hydrogeochemical maps at 1:50,000 scale on paper sheets using traditional printing technologies has been replaced by issuing these on electronic media, in the form of simple information system in HTML format, which is attached on CD or DVD to printed explanatory notes (Fig. 1.14). This simple electronic system has been adapted so that the relevant hydrogeological information is available to each PC user with internet browser. Here, by simple click on the point data (spring, borehole) its parameters are displayed (e.g. discharge, water quality, as seen on Figs. 1.9 and 1.10). It is also possible to print the entire map or its desired part from CD's content. When clicking on the corresponding index of the relevant rock environment, the legend of hydrogeological or hydrogeochemical map is shown where more information can be obtained. The main hydrogeological and hydrogeochemical map of the region (in Annexes 1 and 2 on CD or DVD media attached to the printed explanatory notes) can be, depending on the aerial extent of the region, divided into two or even four detailed maps. A simple click then opens the detailed map. The chosen detailed map (as well as all other windows) are always opened in its upper left corner, and scroll bars on the frame should be used to move to other parts. Holding the cursor over the territory of the detailed maps (but away from hydrogeological objects as springs or boreholes), relevant rock environment description appears just below the cursor in an information tag. Change of desired information source (from hydrogeological to hydrogeochemical maps or vice versa, or hydrogeological cross-section or map legend inspection can be easily performed by the use of rectangular area in the upper left corner of the actually viewed map. According to the aforementioned Directive No. 8/2004-7, associated data annexes in digital format are also attached on the CD / DVD media accompanying the printed explanatory notes. These include the list of documented springs – natural groundwater outlets (both with single measurements of discharge and selected physical and chemical parameters and with long-term discharge gauging and/or monitoring of selected physical and chemical parameters), the list of documented wells and hydrogeological boreholes supplemented by existing gauging results of groundwater levels or piezometric pressures and also the map of hydrogeological documentation in more detailed format as the basic maps, if only selected important hydrogeological objects are shown in the basic hydrogeological map. In the map of hydrogeological documentation all documentation points (springs and boreholes) are present. Analyses of water samples linked with the hydrogeochemical map are also in these attachments, where each analysis has a number identical to the number on the hydrogeochemical map.

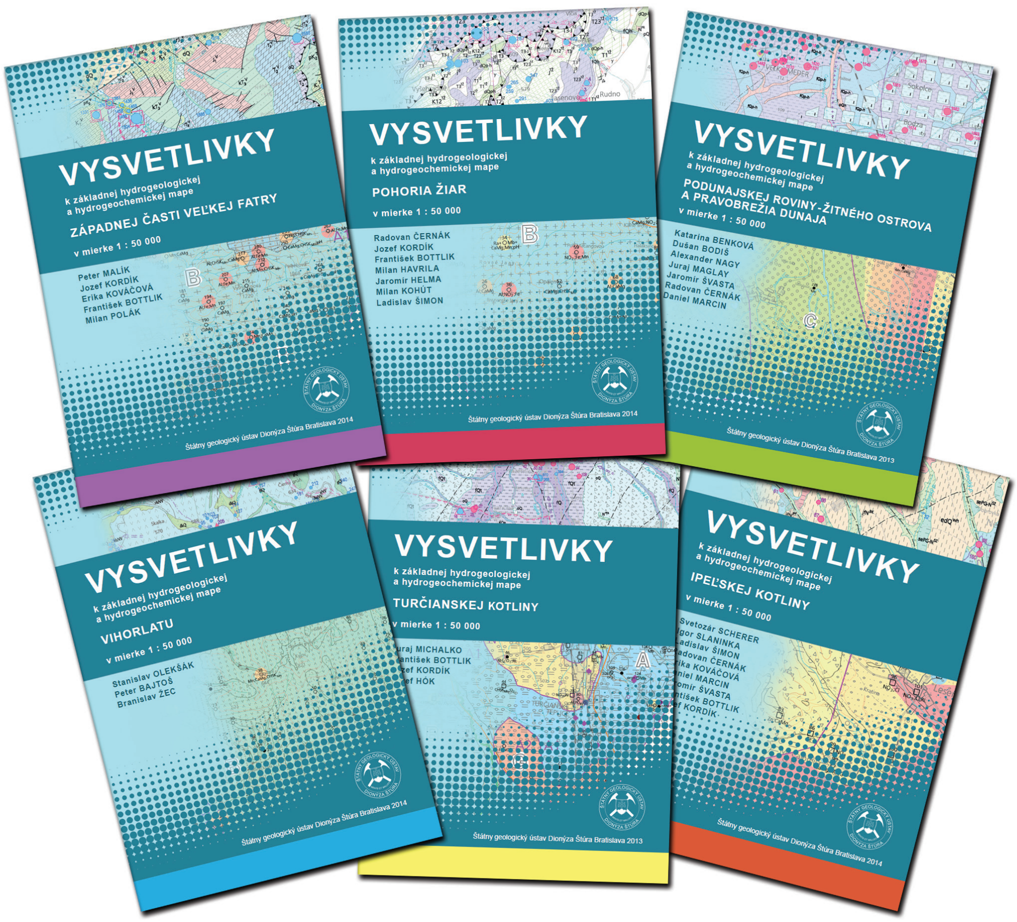

Fig. 1.15 Explanatory notes to the basic hydrogeological and hydrogeochemical maps at a scale of 1:50,000 series issued by SGIDŠ.

So far, SGIDŠ issued explanatory notes to basic hydrogeological and hydrogeochemical maps of the following regions: Turčianska kotlina Basin (Michalko et al., 2013), the region of the Podunajská rovina – Žitný ostrov Lowland together with the right bank of the Danube River (Benková et al., 2013), Medzibodrožie region (Bajtoš et al., 2014), Žiar Mts. (Černák et al., 2014), western part of the Veľká Fatra Mts. (Malík et al., 2014), Ipeľská kotlina Basin (Scherer et al., 2014) and Vihorlat Mts. (Olekšák et al., 2014). SGIDŠ as the publisher intends to keep uniform character of this explanatory notes series as seen on Fig. 1.15.

The future of the basic hydrogeological and hydrogeochemical maps is in their broader use in the direct form of a geographic information system. Here, these maps should be created, presented and transmitted to the users - experts, who can relevantly handle the information contained. The rapid development of groundwater flow modelling methods enabling prompt projection of their results into the relevant geographical area brings also new challenges to future formats of hydrogeological maps. In the future, hydrogeological mapping should consist of georeferenced regional groundwater flow models compilation at regional scales (both quantitative flow models and mass transport models), with the projection of model inputs and outputs to the databases of geographic information systems. Archive data already gathered should be fully referenced by the time of their acquisition and electronic map should enable viewing them on a time line as well. These solutions should also retain the ability of interdisciplinary information exchange (simplicity necessary for data transition to other scientific disciplines and practical applications). In the meantime, sufficient extent of specific technical details (for detailed hydrogeological studies) should be maintained. Georeferenced regional mathematical models of groundwater flow created together with hydrogeological maps information systems should then serve as the basis (initial boundary conditions) for more detailed studies in specific locations.

We hope that information on the hydrogeological and hydrogeochemical settings in individual regions would appropriately serve for correct evaluation of activities that in a given area influence or potentially affect groundwater quantity or quality. Information on the actual use of exploitable groundwater resources or their potential to ensure the drinking water supply would hopefully represent a sufficient knowledge basis for experts who would benefit from them when formulating all serious water management measures or in land-use planning decisions in relevant regions. We hope that basic hydrogeological maps will always be at hand where the importance and presence of groundwater resources would be unacceptably trivialized or misunderstanding of groundwater movement and its dynamics in time would lead to undesirable environmental disasters. At the same time we also hope that presented methods and compilation of basic hydrogeological and hydrogeochemical maps at a scale of 1:50,000 will be saved from conceptual leaps and its further development will be ensured by enthusiastic expert teams involved.

Acknowledgements

The authors gratefully acknowledge the support of the Agency of the Ministry of Education, Science, Research and Sport of the Slovak Republic for the EU structural funds (ASFEU) through the project 'Výskum dopadu klimatickej zmeny na dostupné množstvá podzemných vôd v SR a vytvorenie expertného GIS [Research on the climate change impact on the available groundwater amounts in Slovak Republic and the creation of expert GIS]' ITMS code 26220220002, Operational Programme Research and Development.

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2. Groundwater Quality Presentation in Basic Hydrogeochemical Maps at a Scale of 1:50,000 by Digital Data Treatment Applied in the Slovak Republic

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Abstract: Hydrogeochemical maps have been compiled in Slovakia for more than 40 years. While till 1990 there were issued only print versions of the maps, a new generation of maps, especially since 1994, has been innovated by digital processing of hydrogeochemical information. Uniform principles for their digital imaging are based on the requirements of simplicity, clarity and reproducibility, as well as the relevant Guidelines for the compilation of basic hydrogeochemical maps released by the Ministry of Environment in 2004. The hydrogeochemical maps contain basic information on the chemical composition and quality characteristics of groundwater. The information value of the map has been divided into levels of basic information consisting of qualitative and geochemical (genesis) characteristics of the groundwater, water management criteria and a database of chemical analyses. Therefore the hydrogeochemical maps display three essential criteria, namely: quality (colour in area), geochemistry (raster in the area) and water-management (contour marks - isolines). The quality and water management criteria are derived from the relevant Slovak standards for potable and raw water and geochemical criteria reflect the particular genetic types and chemical types of groundwater. The information value of a new generation of maps is highlighted in a modern approach that is sufficiently custom-friendly to a lay user and the wider scientific community addressing issues of water management.

Keywords: Hydrogeochemistry, hydrogeochemical maps at 1:50,000 scale, groundwater quality, GIS processing, Slovakia

2.1 Introduction

Resources and available volumes of groundwater resources both in the world as well as in Slovakia already cease to be limited only by their quantitative characteristics. In the context of the full-area anthropogenic overburden increased attention is given to their quality characteristics, which are the relevant subjects of the hydrogeochemical maps. A detailed discussion of the history and development of hydrogeochemical mapping in Slovakia was already discussed several times in Slovak literature (e.g. Rapant et al., 1996; Vrana & Rapant, 1999), and therefore we do not deal with it in this paper. We present only the methodology of compiling the hydrogeochemical maps of 1:50,000 (Rapant & Bodiš, 2002), which was developed under the project solution 12-02-9/200 Basic hydrogeological maps of selected regions of Slovakia (Malík, 2006). The methodology is based on the eponymous methodology (Rapant & Bodiš, 1994), by which there were developed in the years 1994 – 1999 the hydrogeochemical maps of seven regions of Slovakia (Malík, 1999; Kordík et al., 2000), between 2002 – 2007 the hydrogeochemical maps for seven regions more and in the years 2007 – 2013 for ten regions of Slovakia. The methodology has reflected knowledge and experience gained in dealing with the above hydrogeochemical maps and amendments to the legal standards and regulations in force in the period of its formation (Ministry Decree No. 29/2002 Coll., later Government Ordinance No. 354/2006 STN 75 7214), which at the time of this paper have been already replaced by new legislative documents (Slovak Government Regulation No. 496/2010 Coll.). In 2004 through the regulations were codified by the issuance of the Directive of the Ministry of Environment No. 9/2004-7, dated October 26, 2004 on the Compilation of Basic Hydrogeochemical Maps.

Significant development of information technology, which by the turn of millennia started to affect almost all areas of human activity, including geology, caused a shift in the methodology for the compilation of basic hydrogeochemical maps closer to the digital way of efficient handling, processing, storage and use of spatial data. In accordance with the "Directive of the Ministry of Environment of the Slovak Republic from April 13, 2000 No. 2/2000 on the Principles of Processing and Transfer of Tasks and Projects in a Geographic Information System (GIS)" there was raised requirement of amendment analogue data and outputs (printed maps, etc.) on digital processing that is the bearer of a more comprehensive and flexible information. One of the limitations of this Directive, however, was its general focus, which did not reflect the specific chara- cteristics of individual geological tasks (Kordík & Slaninka, 2005). In practice, there occurred large differences among submitted outputs of the geological projects of the same or similar focus. For example, for the processing of maps of "Geological Factors of the Environment" (Vrana, 1991) there was not established an uniform binding methodology of results submission in GIS and likewise, compiled basic or thematic hydrogeochemical maps used to offer different information depending on the value of the research team and the purpose of an issue studied. As an example, within the framework of geological research and exploration there was designed GIS spatial database structure information layer for digital vector map in engineering geo- logical zoning of small and medium scales of 1:200,000 and 1:10,000 and in a similar manner have been processed maps of important geological environmental factors, territory susceptibility to landsliding, etc. (Pauditš et al., 2000). The basic principles of compiling digital maps of natural waters quality suggested Kordík & Slaninka (2005).

Based on the current needs of hydrogeochemistry and development of computer technology for the internal needs of the compilation of basic hydrogeochemical maps at a scale of 1:50,000 binding approach was drawn up in the period after 2002 by Kordík & Slaninka (2009), or a form of their digital transfer, taking into account the information value of these map series. The system takes into account the complexity of the information, that the hydrogeochemical map requires and increases its informative value by breaking down data in a relational database with the possibility of interlinking data tables related to the map objects. The way of the information provision pursuant to these principles allows for the use of maps and graphical information in a database, and further analytical and synthetic processing in the sphere of geo-information systems.

2.2 Overview and development of compiling of hydrogeochemical maps issued in Slovakia

As the oldest hydrogeochemical maps of a complex nature can be considered "The groundwater chemistry maps at 1:200,000" which originated as part of the compilation of basic hydrogeological maps at a scale of 1:200,000. During the years 1971 – 1978 these maps covered the entire Slovak territory in manuscript form, and for the whole set of 12 map sheets the same methodology was applied. Printed maps were published a decade later - between 1983 and 1991. Editors of the individual leaves the territory of Slovakia were: map sheet 44 Bratislava – Kullman et al. (1973); map sheet 34 Znojmo – Kullman et al. (1974); map sheet 27 Poprad – Hanzel et al. (1974); map sheet 46-47 Lučenec, Rimavská Seč – Škvarka et al. (1975); map sheet 37 Košice – Hanzel et al. (1975); map sheet 35 Trnava – Kullman et al. (1975); map sheet 38 Michalovce – Škvarka et al. (1976); map sheet 26 Žilina – Zakovič et al. (1976); map sheet 25 Gottwaldov/Zlín – Jetel (1991); map sheet 45 Nitra – Franko et al. (1976); map sheet 28 Svidník – Zakovič et al. (1977) and map sheet 36 Banská Bystrica – Kullman et al. (1978). The authors of the final report on the entire course of the compilation of the basic hydrogeological maps and "maps of the groundwater chemistry" in the scale of 1:200,000 were Kullman & Gazda (1978). Hydrogeochemical maps at 1:200,000 were the first basic information within a comprehensive view of hydrogeochemical conditions. By colours in the polygons chemical types of groundwater according prevailing cations and anions were expressed, by colour intensity degree of total dissolved solids (TDS) of groundwater, the underlying grid and indexes displayed the chemical types of groundwater according the classification by Gazda (1972) and by Roman numerals chemical types of groundwater under Alekin's classification (Alekin, 1970). By independent symbols springs of mineral and thermal waters were displayed, groundwaters of anomalous chemical composition and so on. Since the Slovak Republic has so far been completely covered just by hydrogeological and "hydrogeochemical" maps at 1:200,000, these maps along with explanatory notes (however, prepared only for 6 map sheets) are still a source of the basic information about the hydrogeological and hydrogeochemical conditions of individual regions of Slovakia.

Besides the above maps of groundwater chemistry in the scale of 1:200,000, in the 60s, or 70s of the last century another purpose hydrogeochemical maps were compiled (e.g. Pospíšil & Gazda, 1967; Kullman et al., 1972; Kullman & Gazda, 1973; Hanzel & Gazda, 1973; Orvan et al., 1974; Hanzel et al., 1979, 1981; Dovina et al., 1980; Gazda et al., 1982). In early 80s hydrogeochemical maps were issued mostly as annexes to the final reports of search hydrological surveys (Šalaga et al., 1983; Šalagová et al., 1983). Methods of hydrogeochemical maps compilation at that time were different, and in some cases similar methodical principles were used as in drawing up maps of groundwater chemistry at 1:200,000.

In the next period (before 1991) there were compiled in Slovakia mainly thematic hydrogeochemical maps at a scale of 1:50,000, which formed separate annexes to the final reports of regional hydrogeological research (e.g. Chochol et al. 1984, Kullman et al. 1985, Malík et al. 1986, Malík et al. 1990), or search hydrogeological surveys related to the calculation of natural resources and exploitable groundwater resources (Dovina et al., 1985). Compilation of hydrogeological and hydrogeochemical maps along with explanatory notes was further implemented in the regions of the northern part of Košice Basin and Slanské vrchy Mts. (Jetel et al., 1989), Myjavská pahorkatina Upland, Brezovské and Čachtické Karpaty Mts. (Čechová et al., 1990), Chočské and Skorušinské vrchy Mts. (Dovina et al., 1990), Nízke Tatry Mts. (Kullman et al., 1983; Dovina et al., 1985b; Hanzel et al., 1990), Hornádska kotlina Basin (Jetel et al., 1990), Eastern part of Cerová vrchovina Upland and Rimavská kotlina Basin (Zakovič et al., 1989) and Lučenská kotlina Basin (Škvarka & Bodiš, 1988). Separate hydrogeochemical maps at a scale of 1:50,000 are archived for example in the works of Rapant & Vrana (1983, 1985) and Vrana et al. (1984, 1987).

Compilation of hydrogeochemical maps in the 80s of the last century, in principle, was based on the methodology proposed in the regional geochemical research of groundwater (Vrana & Rapant, 1985 in Gbelský et al., 1985). In these maps colours in the area display the chemical composition of water (distinct, indistinct, mixed types), and rasters display underlying genetic types of groundwater in terms of the classification by Gazda (1974). Contour labels depict, for example, borders of distinct and indistinct chemical composition types, isolines of TDS distribution, etc. Point marks represent the location of sampling sites of common waters and groundwaters, and mineral and thermal waters, if necessary, to which the attached symbols referred to basic information such as the label of the documentation point, the value of TDS, geological labels of aquifers, major components content, etc.

Among the other thematic hydrogeochemical maps typically submitted as attachments to the final reports of search, or preliminary hydrogeological surveys, belong works by Orvan et al. (1981), Halešová et al. (1982), Bačová et al. (1984), Bím et al. (1986), Orvan et al. (1995a,b,c).

Most of these works contain valuable information on the chemical composition and quality of groundwater. The degree of their compatibility with fundamental hydrogeochemical maps at a scale of 1:50,000, compiled since 1994, is however different, due to the fragmentation of methodologies. Part of the map series is valuable and, in many cases in the corresponding period a prestigious documentary material (chemical analyses) archived at the Division of Informatics SGIDŠ, but in most cases it was not digitally processed (personal experience of the authors).

In the period of 1991 – 1993 there were compiled, according to a new uniform methodology first 11 hydrogeological maps at a scale of 1:50,000 (mountain ranges: Branisko, Šarišská vrchovina, Levočské vrchy, Krivánska Malá Fatra, Chvojnická pahorkatina, Spišská Magura, NW slopes of Pezinské Karpaty; basins: Hornonitrianska kotlina, Zvolenská kotlina, Breznianska kotlina; Northern part of Záhorská nížina Lowland). The great pity is that to these maps there were not compiled hydrogeochemical equivalents and review of hydrogeochemical conditions was just part of the explanatory text (Malík et al., 2004).

Following the progress in geochemical information processing using computer technologies and according to the current level of professional approach, in the early 90s of the last century a methodology for the compilation of hydrogeochemical maps at a scale of 1:50,000 was developed (Rapant & Bodiš, 1994). This map generation asked for uniform methodology for hydrogeochemical maps bound with a methodology for hydrogeological maps at the same scale, so that both sets of maps should reflect the qualitative and quantitative characteristics of groundwater in their display area in relation to each other. After a review of methodological principles for drawing up maps based on the experience during the development of the first maps, the methodology for preparing basic hydrogeological and hydrogeochemical maps was finalised (Malík et al., 2003; Rapant & Bodiš 2003; Directive of ME SR No. 9/2004).

From 1994 to 1999 (Malík et al., 2004) basic hydrogeochemical maps of the following regions were compiled within double-sheet set of basic hydrogeological and hydrogeochemical maps at a scale of 1:50,000: Čierna Hora Mts. (Bodiš in Zakovič et al., 1997), Pezinské Karpaty Mts. (Vrana in Hanzel et al., 1999), NE part of Podunajská nížina Lowland (Slaninka in Malík et al., 1999), E part of Veľká Fatra Mts. (Kordík in Malík, Kordík, 1999), S part of Záhorská nížina Lowland (Bodiš, Kordík in Marcin et al., 1995), Ľubovnianska vrchovina Mts. (Jetel, 1999) and N part of Spišsko-gemerské rudohorie Mts. (Slaninka in Scherer et al., 1999). The aim of basic hydrogeochemical maps was to comprehensively identify, describe and evaluate the chemical composition and qualitative characteristics of groundwater. In the maps qualitative and geochemical criteria are primarily spatially expressed. Point marks show the sampling points of groundwater with the specification of the source of groundwater sampling, source type and scope of the analysis. Symbols display additional hydrogeochemical characteristics (anomalous water quality, character of pollutants).

Maps from this series were first completely digitally processed works. In this period, however, the perception of the information value by the individual authors and compilers of maps was diverse. A compromise in providing the information in these maps release was edition on CD in a single information system (Malík ed., 2001). The contents of the CD can be accessed in Windows environments using Internet Explorer (Browser HTML pages). At activating Start.htm the home page opens with a map of Slovakia and shows processed regions. A simple mouse click over selected region, the home hydrogeological map of the region is displayed in which the client can also open the window to display hydrogeochemical maps and explanatory notes. Within the home maps display, interactive viewing of the selected database data of hydrogeological and hydrogeochemical information is enabled.

In terms of methodology by Rapant & Bodiš (1994) within the search hydrogeological survey some other regions were processed, for instance: Mesozoic of W part of Slovenský kras Mts., Železnícke podhorie and part of Licinská pahorkatina Upland (Bodiš in Malík et al., 2000), Vtáčnik and Pohronský Inovec Mts. (Bučeková et al., 2001), Považský Inovec Mts. (Slaninka in Scherer et al., 2004).

In the years 2002 – 2006 there was carried out the compilation of basic hydrogeological and hydrogeochemical maps at a scale of 1:50,000 of the other 9 regions of Slovakia (the "Basic hydrogeological maps of selected regions of Slovakia" Malík, 2006): Medzibodrožie (Bajtoš and Stupák in Bajtoš et al., 2004), Vihorlat Mts. (Bajtoš in Olekšák et al., 2006), Žiar Mts. (Slaninka in Černák et al., 2004), Čergov Mts. (Cicmanová in Marcin et al., 2005), Muránska planina Plateau (Slaninka in Švasta et al., 2004), W part of Veľká Fatra Mts. (Kordík in Malík et al., 2006), Turčianska kotlina Basin (Kordík in Michalko et al., 2005), Ipeľská kotlina Basin (Slaninka in Scherer et al., 2005) and region Podunajská rovina – Žitný ostrov Plain and right bank of the Danube River (Bodiš in Benková et al., 2005). In the years 2007 to 2013 within the project "Basic hydrogeological maps at a scale of 1:50,000" (Malík, 2013) the following basic hydrogeochemical maps of regions were compiled: Žitavská pahorkatina Upland and Pohronský Inovec Mts. (Kordík in Mikita et al., 2011), Slovenský kras Mts. (Kordík in Malík et al., 2013), Rimavská kotlina Basin (Slaninka in Bačová et al., 2012), Bukovské vrchy Mts. (Bajtoš in Bajtoš et al., 2013), Bánovská kotlina Basin (Bodiš and Kordík in Bahnová et al., 2010), Žiarska kotlina Basin (Kordík in Kováčová et al., 2009), Súľovské vrchy Mts. and Žilinská pahorkatina Upland (Slaninka in Marcin et al., 2013), Slovenský raj Mts. (Cicmanová in Bajtoš et al., 2010), E part of Cerová vrchovina Mts. and Gemer terraces region (Slaninka in Švasta et al., 2013) and N part of Podunajská rovina Plain (Bodiš in Bottlik et al., 2013).

2.3 General principles of hydrogeochemical maps compilation

The aim of basic hydrogeochemical maps at 1: 50,000 is to display spatially the most important qualitative and geochemical characteristics of groundwater of the first aquifer at the surface and other major at near-depth. The hydrogeochemical map directly relates to hydrogeological map and expresses and reflects therein mainly qualitative, geochemical, environmental, water management, genetic and prospecting criteria. The hydrogeochemical map is an essential professional basis for characterisation of quality and degree of contamination of groundwater, serving for the rational use and purposeful protection of groundwater.

Basic principles of used concept and cartographic representations of the main hydrogeochemical characteristics consist of Spatial (A), Point marks (B), Symbols (C), Contour markings (D) and Additional maps (E) displays.

A) SPATIAL DISPLAY

In the map are spatially expressed three basic hydrogeochemical criteria, namely:

- Qualitative,
- Geochemical,
- Water management.

QUALITY CRITERIA

Qualitative criteria reflecting the qualitative properties of groundwater are expressed in colour spatial objects based on a comparison of individual analyses of groundwater against defined criteria (see hereinafter) under Government Regulation No. 496/2010 Coll. On the grounds of groundwater division into quality classes the mapped area is divided into areas with the same class of water quality.

GEOCHEMICAL CRITERIA

Geochemical criteria are based on the natural conditions of the region. They are expressed in the form of allocation of hydrogeochemical groups of groundwaters, which are shown with a black grid in the area. Allocated hydrogeochemical groups of water represent regions with the same characteristics of groundwater comprising:

- Genetic types of groundwaters,
- Chemical groundwater types,
- The total dissolved solids of groundwater,
- The nature of the groundwater circulation.

WATER MANAGEMENT CRITERIA

Water management criteria reflect the suitability of raw groundwater in terms of its treatability for drinking purposes. Distinction is made between four categories: A, B, C, D according to STN 75 7214, Water Quality. Raw Water for Treatment at Drinking Water. The territory of a region is segmented through contours and symbols into territories with the same categories of groundwater treatability.

B) POINT MARKS

Point marks show the sampling points of groundwater with the specification of the source groundwater intake, type of source and scope of the analysis.

C) SYMBOLS

They are used to express additional hydrogeochemical characteristics, especially for the display of:

- Groundwater anomalous quality,
- Nature of contaminants and important groundwater components,
- Recommended and advanced analysis of groundwater,
- Time trends in groundwater quality.

D) CONTOUR MARKINGS

They are used to indicate:

- Areas containing elements and components far exceeding the limit values for drinking water,
- Areas with the same category of groundwater treatability,
- Bordered areas with recommended more detailed work.

E) ADDITIONAL MAPS

They are used to express the important additional properties of water, for example:

- Aggressiveness,
- The content of Ca + Mg,
- Other major components of the groundwater by the nature of the mapped area.

2.4 HYDROGEOCHEMICAL CHARACTERISTICS OF THE BASIC DOCUMENTATION MATERIAL

Essential documentary material for the construction of hydrogeochemical maps provide analyses of groundwater samples, i.e. sampling from springs, boreholes, galleries, drainage systems and wells.

A) DOCUMENTATION POINTS DENSITY

For the hydrogeochemical map at 1:50,000 is the mandatory minimum average density of groundwater samples analyses (in a binding analytical range) 1 sample to 3 km^2. In the case of the proposed methodology for the scale of 1:25,000, the recommended average density of water samples analyses ranges from 1 to 1.5 to 1 km^2, and at the scale of 1:200,000 is the recommended density of one sample at 8 km^2. Density of groundwater samples analyses should be considered statistically and has to be adjusted according to natural, human and socio-economic conditions of the mapped area.

B) GROUNDWATER SAMPLING, FIELD MEASUREMENTS AND TESTING

Water sampling was carried out at the time of stable climatic conditions. Samples and other conditions (type and number of sample containers, their sterilization, etc.) should be defined by the laboratory in which the samples are analysed.

The sampling consists of the following tasks performance:

- Measurement - temperature, pH, conductivity (converted to 25 °C), the O_2 content (mg.l^{-1}) and yield (l.s^{-1}),
- Testing - acidity and alkalinity (neutralization titration, or potentiometry),
- Chemical stabilization of the samples in accordance with the instructions of the laboratory.

C) RANGE OF ANALYSES

1. Mandatory: Na, K, Mg, Ca, NH_4, Mn, Fe, F, Cl, SO_4, NO_2, NO_3, PO_4, HCO_3, CO_3, SiO_2, Al, As, Ba, Cd, Cr, Cu, Hg, Pb, Sb, Se, Zn, COD,
2. Recommended: a) organic pollutants,
   b) radiochemical indicators,
3. Extended: microbiological and biological indicators.

Mandatory scope of analyses represent determined range of inorganic components in groundwater within the solution of the Geochemical Atlas of the Slovak Republic, part Groundwater (Rapant & Bodiš 1996) (1 sample/3 km^2) and includes all the major inorganic indicators in terms of the Government Decree No. 29/2002 Coll. In justified cases it is possible to extend analyses purposefully on additional indicators of special inorganic analyses of water.

Analyses of organic pollutants are executed strict-purposely, without any planned density of water sampling in the range of particular groups of indicators – TOC, PAH, AOX, ES, NES. In the case evidently increased content of group characteristics, it is recommended to proceed to analyse specific organic compounds.

Among radiochemical indicators radon is recommended to be analysed with a statistical density of 1 sample/20 km^2 and in the groundwater samples containing radon over 50 Bq.l^{-1} to determine uranium and radium contents.

Microbiological and biological indicators are defined strict-purposely, without any planned density of water sampling in the range of indicators by Ministry Decree No. 29/2002 Coll., particularly from the most important water resources.

D) LIMIT OF DETERMINATION

All analysed water components must be analysed with a margin of about one order of magnitude lower than the standard value in Government Regulation No. 496/2010 Coll.

E) QUALITY AND REPRODUCIBILITY OF ANALYSES

The quality and reproducibility of analyses must be guaranteed by internal and external audit. Internal control is provided in the form of internal laboratory control analyses and in the form of control charts. The external audit is carried out by external control samples and control samples of reference materials in the number of 3 – 7% of the total number of samples.

Analyses of groundwater, not fulfilling the above criteria (mainly in older tests), are used to construct hydrogeochemical maps only as auxiliary. Author of a map assesses individually their significance, reproducibility and validity in time and in appropriate cases, he/she decides on their inclusion in the database analysis of water processed maps.

2.5 Way of map compilation

A) DISPLAY OF GROUNDWATER QUALITY PROPERTIES

Groundwater qualitative properties are expressed through 8 classes of groundwater quality (A to H).

Tab. 2.1 Method of allocation of groundwater quality classes

Groundwater quality properties

Groundwater quality class			
Class label	Class quality characteristics 1	2	3
	+	+	+
	+	+	-
	+	-	+
	+	-	-
	-	+	+
	-	+	-
	-	-	+
	-	-	-

+ meets defined limit values

- doesn't meet defined limit values

Assessed groups of indicators	Assessed indicators	Symbol	Unit	Limit values
1	Aluminium	Al	mg/l	0.2
	Arsenic	As	mg/l	0.01
	Barium	*Ba*	*mg/l*	*1*
	Cadmium	Cd	mg/l	0.003
	Chromium	Cr	mg/l	0.05
	Copper	Cu	mg/l	1
	Mercury	Hg	mg/l	0.001
	Ammonia	NH_4	mg/l	0.5
	Nitrites	NO_2	mg/l	0.1
	Nitrates	NO_3	mg/l	50
	Nickel	Ni	mg/l	0.02
	Antimony	Sb	mg/l	0.005
	Lead	Pb	mg/l	0.01
	Selenium	Se	mg/l	0.01
2	Chlorides	Cl	mg/l	100
	Fluorides	F	mg/l	1.5
	Iron	Fe	mg/l	0.2
	Manganese	Mn	mg/l	0.05
	Phosphates	*PO_4*	*mg/l*	*1*
	Sulphates	SO_4	mg/l	250
	Zinc	Zn	mg/l	3
3	Calcium and magnesium	Ca + Mg	mmol/l	1.1 to 5
	Chem. ox. demand ($KMnO_4$)	COD_{Mn}	mg/l	3
	Magnesium	Mg	mg/l	125
	Oxygen saturation	O_2	%	>50
	Water reaction	pH		6.5-8.5
	Soluble matter	RL	mg/l	1,000

In *Italics* elements are dispayed which are not listed in Ordinance ME SR, No. 29/2002 Coll. on requirements on potable water and its quality control

groundwater of anomalous quality (compared to selected area)

Groundwater quality classes are allocated based on the groupings of limit indicators in terms of Government Regulation No. 496/2010 Coll. into three groups according to their increasing toxicity and complexity of groundwater treatment technology. The method of allocation of groundwater quality classes is shown in Table 2.1. Based on the allocation of individual groundwater samples into classes, the territories are delineated into the areas with the same class of groundwater. The approach requires a minimum of 80% of the membership of the same classes of water quality in the defined area. Groundwater with substantially different qualitative characteristics from the defined area is highlighted by specific symbol as an anomaly.

For colour expression of the groundwater quality "traffic light" method of area display has been selected, from bold blue colour – the area with the best groundwater quality till dark red – the area with the worst groundwater quality characteristics. It is necessary to clearly distinguish "doesn't exceed" of the first group of indicators (metals and toxic forms of nitrogen) by blue and green tones from "exceeds" - red shades of colours.

B) DISPLAY OF GEOCHEMICAL CHARACTERISTICS OF GROUNDWATER

Geochemical characterisation of groundwater is based on an allocation and cartographic delineation of the hydrogeochemical groups of groundwaters. The hydrogeochemical groups are subject to natural conditions of the territory of interest and they are allocated on the basis of genetic types of groundwater, which are further broken down by:

– Groundwater chemical types (according to the Gazda's 1974 characteristics and to the prevailing ions),
– Values of total dissolved solids,
– Geological nature and type of aquifer permeability.

Genetic types of groundwater express the origin of soluble substances. Gazda (1974) distinguished naturally and anthropogenically (Rapant, 2001) conditioned origin of elements and compounds contents in the chemical composition of the groundwater. These properties are amended on Gazda's characteristics (e.g. A_2 distinct, S_2 (SO_4) indistinct, $A_2 – A_1$ intermediary (Gazda, 1972).

The following genetic types and subtypes are distinguished:

1. PETROGENIC:
   a) carbonatogenic,
   b) silicatogenic,
   c) sulphatogenic,
   d) sulphidogenic,
   e) halogenic,
   f) hydrosilicatogenic,
   g) their intermediary types.
2. FLUVIOGENIC
3. MARINOGENIC
4. POLYGENIC
5. ANTHROPOGENIC:
   a) partly anthropogenically affected groundwaters,
   b) anthropogenically affected groundwaters.

As partly anthropogenically affected groundwater such groundwater is delineated, which in its basic chemistry outline (genetic and chemical types) corresponds to geological environment of its circulation, but there occur a partial metamorphosis of the primary chemical composition due to substances and salt influence of anthropogenic origin. This impact is reflected in the increases of TDS (typically in the range 25 – 50%), shifts of the chemical composition towards indistinct types (e.g. from A_2 distinct to A_2 indistinct and intermediary) and the common occurrence of one or several economically important components above the limits under Ministry Decree No. 29/2002 Coll. This groundwater has still a significant proportion of its primarily conditioned chemical composition.

As anthropogenically affected groundwater the groundwater is allocated, which chemical composition and quality characteristics do not correspond to its geological environment circulation. The chemical composition of these groundwaters is heavily altered due to substances and salt of anthropogenic origin. This change is reflected in the change of chemical types (e.g. from the basic to intermediary and mixed ones), increase of total mineralization (usually more than 50%) and regular appearance of several water-management important components exceeding the limits of Government Regulation No. 496/2010 Coll. In these groundwaters it is practically impossible to identify the chemical composition formed by primary processes.

Chemical water types according prevailing ions are expressed by the symbols of elements and components

Tab. 2.2 Scheme of delineation of chemical types according Gazda's characteristics

Type		**Characteristics content in meq.l^{-1} %**	**Example**
basic	distinct	one characteristics > 66	S_1(Cl) dist. S_2(SO_4) dist. A_2 dist.
	indistinct	one characteristics 50 – 66	A_1 indist.
intermediary		two characteristics	A_2-S_2(SO_4) interm. A_1-S_1(Cl) interm. A_2-S_1(SO_4) interm.
mixed		one characteristics 33 – 50 and others < 33	S_1(SO_4) mixed
		all characteristics < 33	A_2-S_1(SO_4)-S_1(Cl) mixed

according to the results of chemical analyses of equivalent values (meq.l^{-1} %) for basic compounds (Na, K, Mg, Ca, NH_4, NO_3, Cl, HCO_3). The criterion for determining the chemical type is equivalent proportion of compounds more than 25 meq.l^{-1} % of the amount 100% of cations and anions, separately. The individual elements and compounds of the chemical composition of groundwaters are arranged according to their equivalent representations.

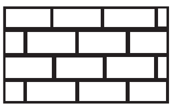
Intervals of values of total mineralization are formed on the basis of mathematical and statistical processing of data, depending on the regional conditions. In the geological features the basic characteristics of the rock environ are specified and permeability type of aquifer. As a basis for allocating groundwater hydrogeochemical groups, genetic types of groundwaters are crucial and the other three characteristics are affiliated to them.

Hydrogeochemical groundwater groups are cartographically illustrated in the form of grid objects. Selection of the grid type must be based on geological structure of the territory of interest, so that genetic types of water comply logically with geological environment of their circulation. For example, for carbonatogenic groundwater of limestones and dolomites "bricks-grid" is used; for silicatogenic crystalline groundwaters grids "+", "x" are used; for silicatogenic volcanites groundwaters "**v**"**-**grid; for fluviogenic water rings, etc. Variations in TDS, chemical types and the type of permeability shall be resolved by marks modifications and marks magnitude.

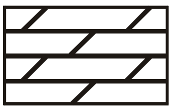
PRINCIPLES AND EXAMPLES OF GRID USE

Petrogenic groundwaters

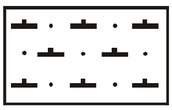
For **carbonatogenic** and **silicatogenic** groundwater grids are used according to the prevailing geological environment forming the chemical composition of the groundwater within the meaning of the guidelines for the compilation of hydrogeological maps of 1:50,000, for example:



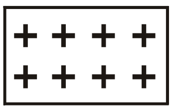
carbonatogenic groundwaters of limestones



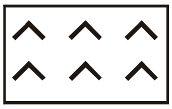
carbonatogenic groundwaters of dolomites



carbonatogenic groundwaters of calcareous sandstones

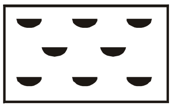


silicatogenic groundwaters of granitoids



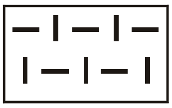
silicatogenic groundwaters of basic effusives

Sulphatogenic groundwaters



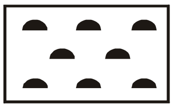
A more detailed rock environ specification of the chemistry formation should be made only in the text to the legend

Sulphidogenic groundwaters



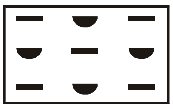
A more detailed rock environ specification of the chemistry formation should be made only in the text to the legend

Halogenic groundwaters



A more detailed rock environ specification of the chemistry formation should be made only in the text to the legend

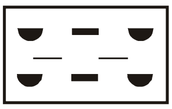
Hydrosilicatogenic groundwaters



A more detailed rock environ specification of the chemistry formation should be made only in the text to the legend

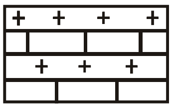
In cases where it is possible and advisable to further specify the nature of the mineralogical and petrographic environment of sulphatogenic to hydrosilicatogenic water, basic grid of these bodies of groundwater is supplemented on mark expressing lithological character of groundwater collectors within the meaning of the compilation of hydrogeological maps at 1:50,000, for example:

sulphidogenic groundwaters of basic neovolcanites

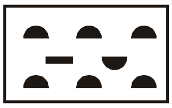


hydrosilicatogenic groundwaters of claystones

Intermediary types are displayed in the form of alternating grids above. Carbonatogenic and silicatogenic nature of groundwater is expressed through the grid according to the predominant environ of the groundwater chemistry formation (in the sense Directive of the Ministry of the Environment 9/2004-7 for the compilation of basic hydrogeochemical maps) and the proportion of present sulphatogenic to hydrosilicatogenic groundwaters is displayed by their basic raster mentioned above, e.g.



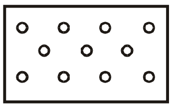
silicate-carbonatogenic groundwaters



hydrosilicate-halogenic groundwaters

silicate-sulphidogenic groundwaters

FLUVIOGENIC GROUNDWATERS



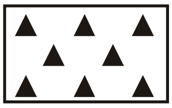
A more detailed rock environ specification of the chemistry formation should be made only in the text to the legend

MARINOGENIC GROUNDWATERS

A more detailed rock environ specification of the chemistry formation should be made only in the text to the legend

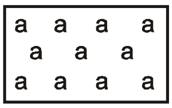
POLYGENIC GROUNDWATERS

Petrogenic-fluviogenic groundwaters

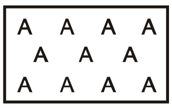


A more detailed rock environ specification of the chemistry formation should be made only in the text to the legend

ANTHROPOGENIC GROUNDWATERS



partly anthropogenically affected groundwaters

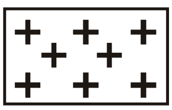


anthropogenically affected groundwaters

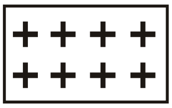
EXAMPLES OF GRIDS AND DESCRIPTION OF HYDROGEOCHEMICAL GROUPS OF GROUNDWATER

HYDROGEOCHEMICAL GROUPS OF GROUNDWATERS

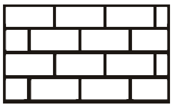
1. Petrogenic



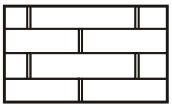
silicatogenic, A_2 basic, less A_2-$S_2(SO_4)$ intermediary, Ca-Mg-HCO_3 and Ca-Mg-HCO_3-SO_4 types, with TDS less than 50 mg.l^{-1}, in granitoids and metamorphites of crystalline, with fissure permeability



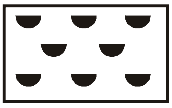
silicatogenic, A_2 basic indistinct, Ca-Mg-HCO_3 type, with TDS 50 – 150 mg.l^{-1}, in granitoids a metamorphites crystalline, with fissure permeability



carbonatogenic, A_2 distinct, Ca-HCO_3 type, with TDS 250 – 400 mg.l^{-1}, in Late Triassic limestones, with karst permeability

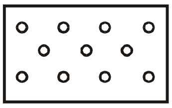


carbonatogenic, A_2 distinct, Ca-Mg-HCO_3 type, with TDS 300 – 500 mg.l^{-1}, in Mesozoic limestones and dolomites, with fissure permeability



sulphatogenic, $S_2(SO_4)$ basic, A_2-$S_2(SO_4)$ intermediary, Ca-Mg-SO_4, Ca-Mg-SO_4-HCO_3 types with TDS more than 1,000 mg.l^{-1}, in Werfen and Keuper sandstone-shale complexes, with fissure permeability

2. Fluviogenic

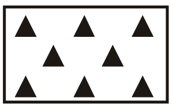


A_2, basic, less A_2-$S_2(SO_4)$ intermediary, Ca-Mg-HCO_3, Ca-Mg-Na-HCO_3-SO_4 type, with TDS 300 – 500 mg.l^{-1}, in fluvial sediments of bottom fill, river terraces, with intergranular permeability

3. Marinogenic

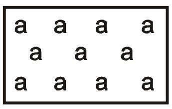
$S_1(Cl)$ basic, $S_1(Cl)$-A_2 intermediary, Na-Cl, Na-Ca-Cl-HCO_3 type, with TDS more than 1,000 mg.l^{-1}, in sands and clays of Eggenburgian, with intergranular-fissure permeability

4. Polygenic

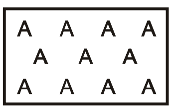


petrogenic-fluviogenic, silicato-carbonatogenic, A_2 basic, Ca-Mg-HCO_3 type, with TDS 400 – 600 mg.l^{-1}, proluvial sediments, with intergranular permeability

5. Anthropogenic



A_2 basic indistinct, A_2-$S_1(Cl)$ intermediary Ca-Mg-HCO_3 a Ca-Mg-Na-HCO_3-Cl types with TDS 500 – 700 mg.l^{-1}, proluvial sediments, with intergranular permeability



A_2-$S_1(Cl)$, A_2-$S_1(NO_3)$ intermediary, Ca-Mg-HCO_3-Cl, Ca-Mg-Na-HCO_3-NO_3 types, in fluvial sediments, with intergranular permeability

C) WATER MANAGEMENT CRITERIA DISPLAY

Water management criteria refer to the adequacy of raw groundwater in terms of its treatability for drinking water. The chemical composition of the groundwater from the sample is compared with the limit concentrations under STN 75 7214 and the category of the treatability is determined (A, B, C, D). Using contours and symbols, the territory is divided into areas with the same category of treatability. 80% representation of the same category of water treatability in the defined area is required.

D) EXPRESSION OF DEEPER COLLECTORS OF GROUNDWATER

Quality properties and hydrogeochemical characteristics of groundwater of major deeper aquifers are displayed through stripes; the width of the stripes depends on the depth level of a collector displayed. A distinction is made in the two following cases:

– The incidence of groundwater of second or third collector,
– presence of different properties of groundwater (a depth) in a single collector.

Alternation of horizontal stripes indicates:

– Qualitative properties of groundwater - groundwater quality classes (point 4.A),
– geochemical characteristics of groundwaters – hydrogeochemical groups of groundwaters (point 5.B).

Groundwater of the Ist aquifer, or Ist groundwater table level within a single aquifer depicts a horizontal stripe whose width corresponds to the width of the base grid of hydrogeochemical groups.

Groundwater of the IInd aquifer (located up to a depth 100 m), or groundwater level depth up to 100 m in one aquifer is depicted by a strip whose width is equal to 1.5 times of the width of the base grid of hydrogeochemical groups of groundwaters.

Groundwater aquifer located deeper than 100 m, or groundwater level depth of over 100 m in one aquifer is depicted by a strip whose width is doubled compared to the basic grid hydrogeochemical groups of groundwaters.

In the case of changed quality properties of groundwater with a depth and hydrogeochemical characteristics of the groundwater do not change with depth – the colour strips alternation indicates only change in the groundwater quality. Similarly, if the qualitative properties of groundwater in the overlying and underlying collectors do not change and there is only a change of hydrogeochemical characteristics of groundwater, alternating stripes of different grids show the incidence of various hydrogeochemical groups of groundwater.

Areas with several major collectors in different depth groundwater horizons:

1	Ist groundwater aquifer
2	2nd groundwater substrate collector horizon to a depth of 100 m
3	3rd groundwater substrate collector horizon at a depth above 100 m

E) POINT MARKS

Point marks are used for determining the location of groundwater sampling for chemical analysis with specification of the source and the number corresponding to the number of analysis in the database. The sampling points are ranked according to ascending x-axis of the sampling point(s).

spring

borehole

well

drainage

gallery

Mineral and thermal waters shall be expressed by the above marks. In the case of mineral water dark purple colour is used, in the case of thermal waters dark blue colour is used.

mineral water spring

borehole with thermal water

F) SYMBOLS

The symbols are used to express additional hydrogeochemical characteristics:

– anomalous groundwater quality,
– the nature of contaminants and important water compounds,
– recommended and extended scope of groundwater analyses,
– temporal evolution of groundwater.

Groundwaters of anomalous quality

Groundwater resources substantially different in their qualitative characteristics (at least on 2 classes) from defined groundwater quality class are plotted by ring of 8 mm size and colour of appropriate quality.


groundwaters of ***D*** quality class

Display of contaminating compounds character

Character of exceeding the limit values of a binding scope of groundwater analyses above criteria of Government Regulation No. 496/2010 Coll. is expressed by the symbol of exceeded compound right up to point mark of

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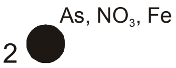
sampling point. In the case of several exceeded indicators only the three most exceeded ones are displayed, depending on their degree of toxicity.

source of groundwater containing As>0.01 $mg.l^{-1}$



source of groundwater containing As>0.01 $mg.l^{-1}$, NO_3>50 $mg.l^{-1}$ and Fe>0.2 $mg.l^{-1}$

Display of recommended and expanded scope of analyses

Analyses of groundwater samples with recommended and expanded scope are expressed by the symbol of analysis scope placed at the bottom right of indications of water sampling. In the case of exceeding the limit indicators of analysed substances the symbol is highlighted.

org analysed organic substances, limit values under Government Regulation No. 496/2010 Coll. not exceeded

org analysed organic substances, limit values under Government Regulation No. 496/2010 Coll. exceeded

Ra analysed radiologic indicators, indicative values under Regulation of the MoE SR No. 12/2001 Coll. not exceeded

Ra analysed radiologic indicators, indicative values under Regulation of the MoE SR No. 12/2001 Coll. exceeded

Mb analysed microbiologic and biologic indicators under Government Regulation No. 496/2010 Coll. not exceeded

Mb analysed microbiologic and biologic indicators, under Government Regulation No. 496/2010 Coll. exceeded

DISPLAY OF TEMPORAL EVOLUTION OF GROUNDWATER QUALITY

Time evolution of the groundwater quality is expressed in groundwater resources with multiple repeated monitoring of the chemical composition (at least 5 analyses within a time span of at least five years). Character of such groundwater sources in the map is displayed by a light brown arrow through the centre of the point mark of sampling.

Character of groundwater temporal change


stable


improvement


worsening

POINTS OF CONTAMINANTS TRANSFER TO THE AQUIFER

The areas are displayed where transfer of pollutants into aquifers has been confirmed, or assumed. The nature of these places is expressed in map by dark red double arrow in the direction of contamination spread. By the symbol nature of the contaminant is displayed.

Transfer of contamination to aquifers

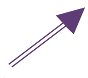
identified

assumed

GROUNDWATERS DYNAMICS

Dynamic characteristics of groundwater are expressed by groundwater flow direction in the first aquifer and the direction of flow of water in significant deeper situated collector in hydrogeochemical section. Groundwater flow direction is expressed on the map by violet arrow.


flow direction in the first aquifer


flow direction in deeper situated collector in hydrogeochemical section

G) CONTOUR MARKS

Contour marks are used for:

– Display of spatially defined characteristics of groundwater,
– an indication of the quality characteristics – quality classes of surface waters,
– border areas with increased content of contaminants,
– definition of the territory of recommended for more detailed works,
– display of hydrogeochemical section.


boundaries of defined hydrogeochemical groups of groundwater

areas containing chemical elements and components in excess of the Government Regulation No. 496/2010 Coll., by the symbol the elements/components are indicated

quality class of surface waters

limit category of groundwater treatability

Quality class of surface water shall be indicated by the streams observed in the national monitoring network. The map displays the resulting class of surface waters (I to V) under STN 75 7221, Surface water quality classification.

area recommended for more detailed works

The areas are depicted, where based upon the achieved results, more detailed works are recommended – surveying, monitoring, restoration and so on. The nature of the proposed work shall be indicated in the text of the explanatory notes to the map.

H) ADDITIONAL MAPS

Through additional maps at a scale 1:200,000 to 1:500,000, other important additional information on the chemical composition of groundwater in the mapped area shall be expressed, or, depending on the availability of data on the properties of precipitation or surface water. The additional maps in form of mono-element colour maps, or isolines reflect the spatial distribution of concentrations of the component under study.

The maps reflect additional spatial distribution of economically important groundwater components, namely:

a) aggressiveness,
b) the content of Ca + Mg (hardness),
c) the content of nitrates,
d) category of treatability under STN 75 7214,

and other groundwater compounds, according to the nature of natural waters in the mapped area.

I) HYDROGEOCHEMICAL SECTION

The aim of the hydrogeochemical section is to express zoning and spatial characteristics of the chemical composition and qualitative properties of groundwater. The hydrogeochemical section is compiled mainly in the areas with several aquifers, or in the areas where the aquifer hydrogeochemical zonation has been observed. The section is depicted on a joint sheet with the map and its scale (length, height) is possible to magnify two to five times according to the need for transparency and clarity, compared to the scale of the map. The scale of section is marked on the map sheet. In the hydrogeochemical section are displayed the prevailing hydrogeochemical characteristics listed in the map, and in particular:

– hydrogeochemical groups of groundwater,
– groundwater quality classes,
– dynamics of chemical composition and qualitative properties of groundwater (groundwater flow direction, spread and her character).

A ——— A´ line of hydrogeochemical section

TOPOGRAPHIC GROUND DOCUMENT

Hydrogeochemical map is compiled into a simplified topographic document shown in grey. Topography includes:

– river network,
– topography (definition and description of towns and municipalities),
– simplified altimetry (designation and name of the altitude points, contours each 50 meters).

TEXT EXPLANATIONS

Explanatory notes are component of each map. Text explanations include:

– summary of natural conditions (in the case, when the hydrogeochemical map is prepared in parallel with the hydrogeological map, they are not described),
– level of hydrogeochemical survey,
– character of reproducibility of the used hydrogeochemical documentation material,
– characteristics of the processes of formation of the chemical composition of the groundwater of the region (including anthropogenic factors)
– characteristics and classification of the chemical composition of the groundwater,
– characteristics of qualitative properties of groundwater,
– detailed characteristics of the territories proposed for further more detailed work and the justification of the proposed works.

HYDROGEOCHEMICAL DOCUMENTATION

The hydrogeochemical map and the annexed text part are inextricably linked containing the documentary material used in their preparation. Hydrogeochemical documentary materials represent the analyses of groundwater samples used to construct hydrogeochemical maps. Each analysis has a number identical to the number specified in the hydrogeochemical map. On the map and in the database analyses are listed in the order of the increasing x-axis. In addition to the results of analytical data and field measurements there are shown the date of groundwater sampling, coordinates, sampling sites and resources.

2.6 PRINCIPLES OF COMPILING UNITE DIGITAL GROUNDWORK OF THE HYDROGEOCHEMICAL MAPS AT A SCALE OF 1:50,000

In order to achieve unified submission of the results of basic hydrogeochemical maps it was compiled a mandatory internal procedure, in which the emphasis is also on digital presentation of information value of map series (Kordík & Slaninka, 2009). Single procedure assumes that all the basic information listed in the hydrogeochemical map can be processed as separate thematic layers that consist of graphics, database and descriptive digital data. According to the rules of compiling information systems (Directive of the Ministry of Environment of the Slovak Republic from April 13, 2000 No. 2/2000 on the Principles of Processing and Transfer of Tasks and Projects in Geographic Information Systems) the unity of thematic layers must be preserved in the method of displaying objects in the layer (point, line, polygon) and in the way it is characterized in the connected database. As main information base layers of the hydrogeochemical maps are considered:

• groundwater qualitative properties,
• geochemical characteristics of the groundwater circulation in the environment,

- water management characterization of groundwater,
- database of the chemical composition of groundwater.

As required by the Directive No. 9/2004 of the Ministry of the Environment on the Compilation of Basic Hydrogeochemical Maps among additional required information in the hydrogeochemical map belong mainly point marks and symbols (local sources of anthropogenic pollution, anomalous groundwater quality, nature of groundwater pollutants and relevant constituents and others), line and contour objects (e.g. bounding of spatially defined characteristics) and additional maps indicating the distribution of economically important constituents in water.

INFORMATION LAYER – GROUNDWATER QUALITATIVE PROPERTIES

Qualitative properties of groundwater are shown by the colour of an area (polygon, surface entity), based on a comparison of individual analyses of groundwater with the criteria defined under Government Regulation No. 496/2010 Coll., laying down requirements for water intended for human consumption. On the grounds of groundwater quality classes defined, the mapped area is divided into areas with the same class of water quality; up to eight classes of groundwater quality (A to H) can be defined. Each basic thematic unit, which represents the possible combinations of eight classes of groundwater quality, has in the column *kvalita_ID* quality label in the map (tab. 2.3). As the graphic entities with the same class of groundwater quality may not contain identical information on qualitative characteristics and nature of environmental pollution (in the field *kvalita_popis*), for this thematic layer the code table is not proposed. Through field *kvalita_vyclenenie* additional information on how allocation of groundwater quality classes can be obtained, in particular information on the physico-chemical parameters and limit values in the waters which are the most important in terms of allocation of classes. Example of the information presented on the qualitative properties of the groundwater is shown in Fig. 2.1. The darkest red area in Fig. 2.1 expresses an example of the worst H quality class due to municipal and agricultural pollution.

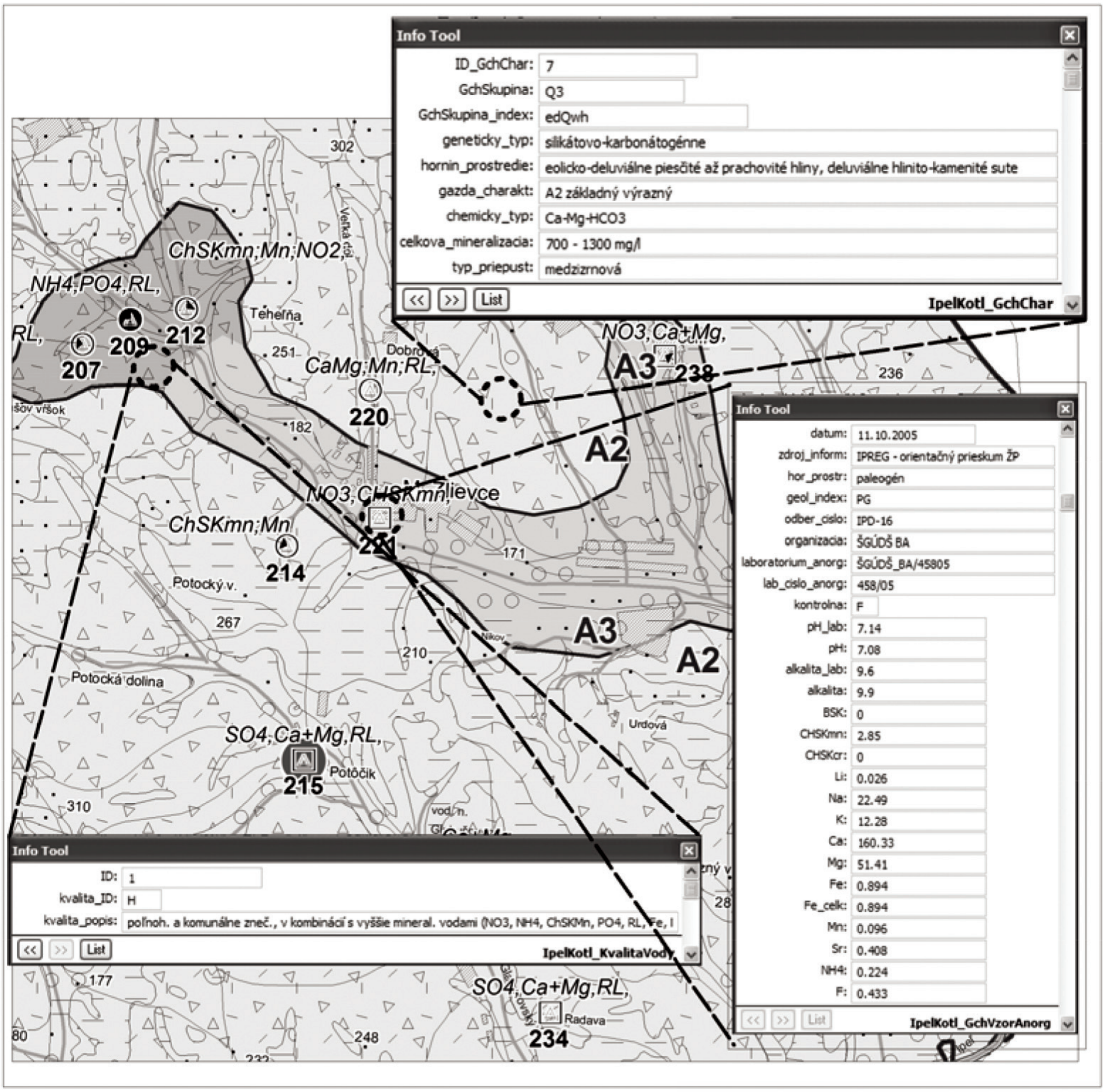


Fig. 2.1 Example of presented information obtained from basic hydrogeochemical map at a scale 1:50,000 (following Slaninka in Scherer et al., 2005)

Tab. 2.3 Structure of information layer "Qualitative properties of groundwater"

Field designation	Data type	Characteristics and description of data field
ID	Integer	Unique database identifier of graphical entities (1...n)
kvalita_ID	Char(2)	Class designation of groundwater quality on the map (A to H)
kvalita_popis	Char(200)	Description of the qualitative characteristics and nature of pollution
kvalita_vyclenenie	hyperlink	Link to a diagram of allocation of groundwater quality classes under Rapant, Bodiš (2003)

INFORMATION LAYER – WATER MANAGEMENT CHARACTERISTICS OF GROUNDWATER

Water management criteria refer to the adequacy of raw groundwater in terms of its treatability for drinking water. The chemical composition of groundwater from individual samples is compared to the cut-off concentration given in the Regulation No. 636/2004 of the Ministry of Environment Coll. laying down requirements for raw groundwater quality and groundwater quality monitoring at public water supplies and the category of the treatability is determined. In the former STN 75 7214 the treatability was divided into categories A, B, C, D; in the Regulation No. 636/2004 it is divided in categories A1, A2, A3). Using contours and symbols the area is divided into territories with the same category of groundwater treatability. Each thematic base unit, which represents possible combinations of the four criteria of water treatment (A1, A2, A3, or untreatable groundwater), is indicated in the field *vodohosp_krit_ID* code 1-4 (Tab. 2). More detailed information on water management characteristics of groundwater is expressed in the description of the particularities of the environment (*vodohosp_krit_popis*).

Tab. 2.4 Structure of information layer "Groundwater characteristics for water management"

Field designation	Data type	Characteristics and description of data field
ID	Integer	Unique database identifier of graphical entities (1...n)
vodohosp_krit_ID	Integer	Code of environmental characteristics (1...4)
vodohosp_krit _popis	Char(254)	Description of the particularities of the environment

INFORMATION LAYER – GEOCHEMICAL CHARACTERISTICS OF THE ENVIRONMENT OF GROUNDWATER CIRCULATION

Geochemical characterisation of groundwater circulation environment is based on the natural conditions of the region. It is expressed through the delineation of hydrogeochemical groups of groundwaters, which are shown on the map by black patterns in the area. The allocated hydrogeochemical groups of groundwater represent areas with the same genetic and chemical types, a range of values of total water mineralization and similar properties of geological environment of groundwater circulation. Genetic types of groundwater express the origin of soluble substances. A distinction is natural (Gazda, 1974) and anthropogenic (Rapant, 2001) conditional origin content of elements and components of the chemical composition of the groundwater. They are amended on Gazda`s characteristics (e.g. A_2 distinct, $S_2(SO_4)$ indistinct, $A_2 – A_1$ intermediary type of groundwater – Gazda (1972). Based on the prevailing ions the chemical water types are expressed by the symbols of elements and components according to the results of chemical analysis, for example, Ca-HCO_3 type. Intervals of values of total mineralization are broken down on the basis of mathematical and statistical data processing. The geological characteristics contains basic characteristics of the rock environ type and permeability of aquifer. It follows that each basic thematic unit (Tab. 2.5) describes the origin of dissolved solids in water (fields *geneticky_typ* or *Gazda_charakt*), chemical water type (field *chemicky_typ*), prevailing values of total mineralization (field *celkova_mineralizacia*) and collector bedrock (field *hornin_prostredie*). Information on the collector`s rock environment must be linked with

Tab. 2.5 Structure of information layer "Geochemical characteristics of aquifer"

Field designation	Data type	Characteristics and description of data field
ID	Integer	Unique database identifier of graphical entity
GchChar_ID	Integer	ID of geochemical characteristics, according to legend of geochemical characteristics of specific map (1 - n / number of delineated groups)
geneticky_typ	Char(20)	Expresses origin of the soluble substance (natural or anthropogenic)
gazda_charakt	Char(30)	Gazda`s characteristics of groundwater (e.g. A_2 distinct, $S_2(SO_4)$ indistinct, A_2-A_1 intermediary type of groundwater)
chemicky_typ	Char(30)	Chemical type of groundwater under prevailing ions is expressed in the symbols of elements and components according to the results of chemical analyses
celkova_mineralizacia	Char(20)	Interval of total mineralization values based on mathematical and statistical processing of data
hornin_prostredie	Char(200)	Basic characteristics of the rock environ (age, stratigraphic affiliation, lithologic-petrographic character) type and permeability of aquifer

the information in the relevant basic hydrogeological map. Example of information provided under this thematic layer is shown in Fig. 2.1, which displays geochemical group Q3 (petrogenic silicate-carbonatogenic TDS groundwater with A_2 basic distinct, Ca-Mg-HCO_3 type of chemical content).

INFORMATION LAYER – DATABASE OF CHEMICAL COMPOSITION OF GROUNDWATER

Database of the chemical composition of groundwater is very important in terms of methodology and mandatory part of the map presenting the results of research and exploration. Database presents documentary material representing mainly chemical analysis of groundwater samples used to construct the hydrogeochemical map. Significant information value that the primary database presents, is subject to several limitations, which are necessary to take into account at the breakdown and structuring of relational database of chemical composition (chemical analyses are obtained from various sources, contents of chemical parameters representing different periods of time, samples are analysed in different laboratories or by various analytical methods, etc.). When interpreting these data, it is therefore important to assess and express the relevance of the information obtained.

Database of the chemical composition of the groundwater is interactively assigned to point marks of groundwater sampling points (point entities). Given the complexity of hydrogeochemical information it is inevitable to build up geochemical relational database. Scheme of relational linking of database tables representing the chemical composition of water, or hydrochemical database structure has been extensively discussed in Kordík & Slaninka (2009). Hydrochemical database structure for the purposes of the compilation of basic hydrogeochemical maps at a scale of 1:50,000 is an intermediate step in the preparation of a comprehensive information system of geological information that is continuously implemented at SGIDŠ. Example of the information on the chemical composition of groundwater is shown in Fig. 2.1.

2.7 CONCLUSIONS

Basic or various thematic hydrogeochemical maps represent the initial background information on the chemical composition and quality of groundwater in Slovakia. The significant development of information technology, especially after 1991, greatly influenced the development of hydrogeochemical presentation of information in Slovakia. While up to 1991 there were built in our practice only traditional forms of printed hydrogeochemical maps, after 1991 a shift has been experienced, mainly in the direction of compiling digital maps and later also in the direction of building information systems to the relevant map series.

The oldest hydrogeochemical maps of the complex nature compiled by unified methodology may be considered "Maps of the chemistry of groundwater in the scale of 1:200,000" which originated as part of the compilation of basic hydrogeological maps at 1:200,000 mainly in the 70s of the last century (in total 12 map sheets). Other mostly thematic hydrogeochemical maps compiled in the period before 1980, were marked by inconsistency of methodical processing of hydrogeochemical information, while hydrogeochemical maps elaborated in the 80s of last century, in principle, were based on a methodology proposed in regional geochemical research of groundwater (Vrana & Rapant, 1985 in Gbelský et al., 1985).

The first map works completely processed into digital data were carried out within the assembled two-sheet basic hydrogeological and hydrogeochemical maps at a scale of 1:50,000 in the years 1994 – 1999 for 7 regions of Slovakia (hydrogeochemical part was processed according to the methodology Rapant & Bodiš (1994), later modified in 2003). The problem with the first digital data, however, was a different view of individual authors of maps to digital information value of the information provided. It was therefore necessary to develop at SGIDŠ a binding procedure for the compilation of basic hydrogeochemical maps at a scale of 1:50,000, or presentation of these maps in digital form and in the form of a simple information system (Kordík & Slaninka 2009).

Basic hydrogeochemical maps display the most important quality and geochemical characteristics of groundwater of the first aquifer, eventually other major deeper aquifers. For main information base layers of the hydrogeochemical maps have been proposed:

- groundwater qualitative properties,
- water management characterization of groundwater,
- geochemical characteristics of the groundwater circulation environment,
- database of the chemical composition of groundwater.

Each of these thematic layers contains in addition to a unique database identifier and the designation of the relevant characteristics of groundwater or the environment of circulation also descriptive information, very valuable for users of hydrogeochemical information. The practice has proved the need for interconnection of hydrogeological and hydrogeochemical information; quantitative and qualitative parameters of the rock environment and groundwater circulating in it are therefore displayed on two-sheet basic hydrogeological and hydrogeochemical maps. The compilation of text explanations to these maps also follows the above principles pursuant to the Regulation No. 8/2004-7 of the Ministry of Environment of the Slovak Republic on Compilation of basic hydrogeological maps at 1:50,000, the explanations are processed into one text whole with interrelated and clearly defined content.

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(BSK)]' ITMS code 26240220059, Operational Programme Research and Development.

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3. Hydrogeological Boreholes and Wells Database and its Use on Regional Rock Permeability Determination

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Abstract: In the archive of the State Geological Institute of Dionýz Štúr, a collection of some 18,000 manuscript records on hydrogeological surveys have been gradually built up. Since 1970's, records on reported hydrogeological boreholes and wells were gradually abstracted into unified paper formats. With the start of the new millennium, a digital borehole database was created. Having necessary data for doing this, regional values of transmissivity coefficient *T* and hydraulic conductivity *K* data could be derived from specific capacity data on pumping tests from boreholes and wells. Using complex re-interpretation process, eliminating influences of differently performed pumping tests and taking into account hydraulic resistivities, both of wells and aquifers, specific capacity data could serve as relatively good source for hydraulic properties estimation. These were performed for 106 different aquifer types, using data from 16,239 individual pumping tests on boreholes. Comparison of the resulting regional distribution of hydraulic properties with frequently applied classification scales for these parameters shows that mean regional values can be found in relatively narrow intervals, while individual boreholes and well can differ from each other in a broad spectrum of values.

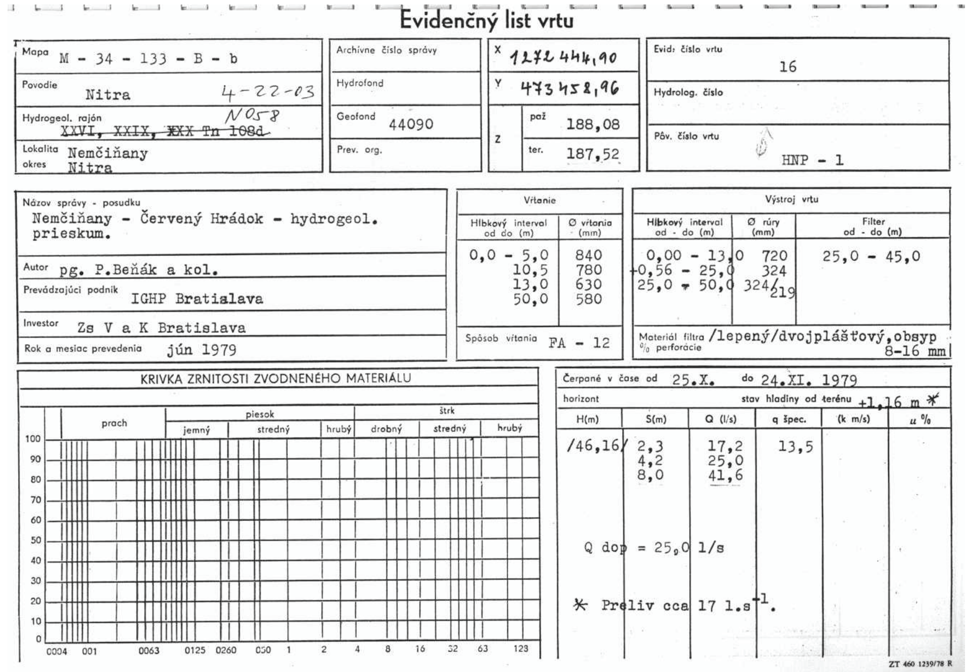
Keywords: hydrogeological boreholes, database of wells, specific capacity, transmissivity, hydraulic conductivity, Slovak West Carpathians

3.1 Introduction

Reliable information on groundwater amounts, groundwater quality and aquifer properties represent inevitable condition for proper assessment of hydrogeological settings from the detailed local scales to the generalised country overviews. Gathering relevant information in the former Czechoslovakia started relatively early, with the legal support of Geological Act. Due to this, a state institution of Geofond was created in the 1970's, in charge of collecting manuscript reports from all geological activities in the country, creation of which and passing them to Geofond was obligatory. The Geofond, since 1995 incorporated into the State Geological Institute of Dionýz Štúr (SGIDŠ) since that time still maintains a huge manuscript archive of all kinds of geological reports. In 2016, in this archive a collection of some 18,000 manuscript records on hydrogeological surveys is registered. These reports, mostly local hydrogeological surveys, contain valuable information on artificial hydrogeological objects – results of technical activities (mostly drillings) undertaken in terms of groundwater abstraction or monitoring. Since 1970's, records on reported hydrogeological boreholes and wells were gradually abstracted from manuscript reports and archived on uniformly formatted paper register cards. With the start of digital era, a digital borehole database was gradually developed. Nowadays (spring 2016), records from 25,323 wells and boreholes are stored there. The database of hydrogeological boreholes and wells today is one of the most extensively used source of information on the Department of Hydrogeology and Geothermal Energy of SGIDŠ. It is being continuously updated as new reports are arriving into the Central Geological Archive of SGIDŠ. Every day hydrogeologists enter the database by means of the common interface or access the raw data from within GIS applications. Although many reported data are lacking (unintentionally, by scope of the problem or even intentionally) some important data on groundwater or rock environment, this database represents a valuable source of hydrogeological information in many aspects. Apart from other parameters, 16,729 pumping tests on boreholes could be found here, analysed and reinterpreted for rock hydraulic properties assessment, both for individual boreholes and for the pumped aquifers. In the database if possible, each borehole was linked to a certain geological type of pumped aquifer according to screen position (open casing interval). Using the digital geological map of Slovakia in the scale of 1:50,000 (Káčer et al., 2005; Map server of the SGIDŠ 2016), 156 general hydrogeological types of aquifers were delineated (Malík et al., 2007). In Quaternary deposits, 31 Quaternary sedimentary aquifer types were identified and in pre-Quaternary rocks outcropping on the territory of the Slovak Republic, 125 pre-Quaternary aquifer types were delineated. As described within the paper, basic hydraulic properties of these aquifers (hydraulic conductivity ***K*** and transmissivity ***T***) were examined and attributed to them. After completion of this interpretation process, acquired regional values of hydraulic parameters are discussed in terms of existing classifications, heterogeneity and distribution patterns.

3.2 Database of hydrogeological boreholes

The central geological archive of the SGIDŠ contains thousands of reports on hydrodynamic tests performed on almost all wells drilled over the territory of Slovakia since 1926. Starting from the 1970's, well tests from these reports are being summarized and archived on register cards. Example of such cards is on Fig. 3.1 and Fig. 3.2. The Department of Informatics of SGIDŠ later had transcribed some parts of these cards into a set of four interconnected


Evidenčný list vrtu

Mapa	M - 34 - 133 - B - b
Povodie	Nitra 4-22-03
Hydrogeol. rajón	XXVI, XXIX, XXX Tn 108d N058
Lokalita, okres	Nemčiňany, Nitra
Archívne číslo správy	
Hydrofond	
Geofond	44090
Prev. org.	
X	1272444,90
Y	473458,96
Z – pož	188,08
Z – ter.	187,52
Evid. číslo vrtu	16
Hydrolog. číslo	
Pôv. číslo vrtu	HNP - 1
Názov správy - posudku	Nemčiňany - Červený Hrádok - hydrogeol. prieskum.
Autor	pg. P.Beňák a kol.
Prevádzajúci podnik	IGHP Bratislava
Investor	Zs V a K Bratislava
Rok a mesiac prevedenia	jún 1979
Spôsob vŕtania	FA - 12
Materiál filtra / % perforácie	/lepený/dvojplášťový,obsyp 8-16 mm

Vŕtanie – Hĺbkový interval od do (m)	Ø vŕtania (mm)
0,0 - 5,0	840
10,5	780
13,0	630
50,0	580

Výstroj vrtu – Hĺbkový interval od - do (m)	Ø rúry (mm)	Filter od - do (m)
0,00 - 13,0	720	25,0 - 45,0
+0,56 - 25,0	324	
25,0 - 50,0	324/219	

KRIVKA ZRNITOSTI ZVODNENÉHO MATERIÁLU

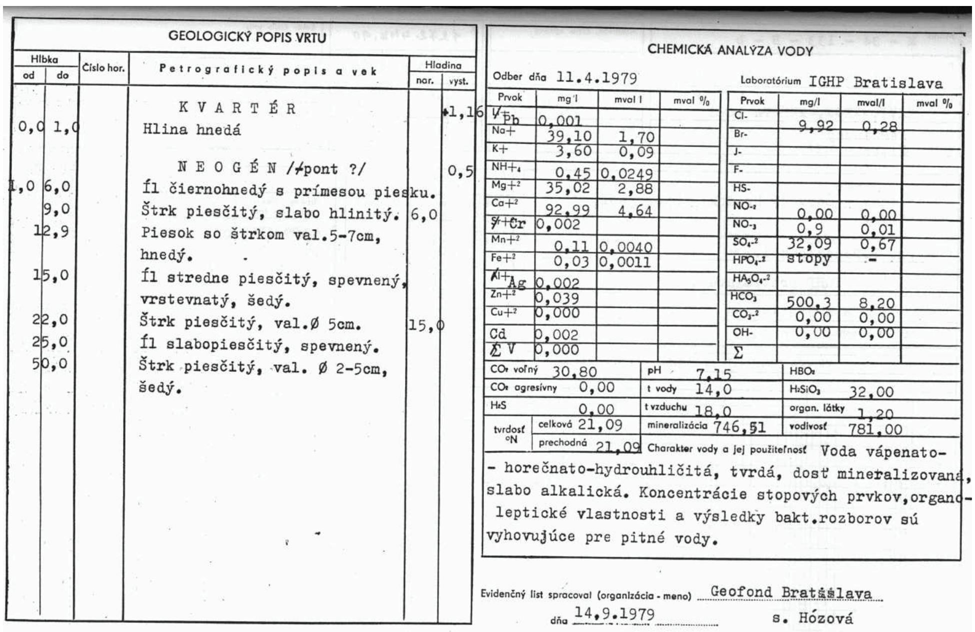
Čerpané v čase od 25.X. do 24.XI. 1979, horizont, stav hladiny od terénu +1,16 m *

H(m)	S(m)	Q (l/s)	q špec.	(k m/s)	α %
/46,16/	2,3	17,2	13,5		
	4,2	25,0			
	8,0	41,6			

Q dop = 25,0 l/s

* Preliv cca 17 l.s-1.

Fig. 3.1 Example of a hydrogeological borehole register card, 1st page.


GEOLOGICKÝ POPIS VRTU

Hĺbka od	do	Číslo hor.	Petrografický popis a vek	Hladina nar.	vyst.
			KVARTÉR		+1,16
0,0	1,0		Hlina hnedá		
			NEOGÉN /pont ?/	0,5	
1,0	6,0		fl čiernohnedý s prímesou piesku.		
	9,0		Štrk piesčitý, slabo hlinitý.	6,0	
	12,9		Piesok so štrkom val.5-7cm, hnedý.		
	15,0		fl stredne piesčitý, spevnený, vrstevnatý, šedý.		
	22,0		Štrk piesčitý, val.Ø 5cm.	15,0	
	25,0		fl slabopiesčitý, spevnený.		
	50,0		Štrk piesčitý, val. Ø 2-5cm, šedý.		

CHEMICKÁ ANALÝZA VODY

Odber dňa 11.4.1979 — Laboratórium IGHP Bratislava

Prvok	mg/l	mval/l	Prvok	mg/l	mval/l
Pb	0,001		Cl-	9,92	0,28
Na+	39,10	1,70	Br-		
K+	3,60	0,09	J-		
NH4+	0,45	0,0249	F-		
Mg+2	35,02	2,88	HS-		
Ca+2	92,99	4,64	NO2-	0,00	0,00
Cr	0,002		NO3-	0,9	0,01
Mn+2	0,11	0,0040	SO4-2	32,09	0,67
Fe+2	0,03	0,0011	HPO4-2	stopy	-
Ag	0,002		HAsO4-2		
Zn+2	0,039		HCO3	500,3	8,20
Cu+2	0,000		CO3-2	0,00	0,00
Cd	0,002		OH-	0,00	0,00
Σ V	0,000		Σ		

CO2 voľný 30,80; pH 7,15; HBO2
CO2 agresívny 0,00; t vody 14,0; H2SiO3 32,00
H2S 0,00; t vzduchu 18,0; organ. látky 1,20
tvrdosť °N celková 21,09; prechodná 21,09; mineralizácia 746,51; vodivosť 781,00
Charakter vody a jej použiteľnosť: Voda vápenato-horečnato-hydrouhličitá, tvrdá, dosť mineralizovaná, slabo alkalická. Koncentrácie stopových prvkov, organoleptické vlastnosti a výsledky bakt.rozborov sú vyhovujúce pre pitné vody.

Evidenčný list spracoval (organizácia - meno) Geofond Bratislava, dňa 14.9.1979, s. Hózová

Fig. 3.2 Example of a hydrogeological borehole register card, 2nd page.

tables in dBase format, which laid the basis for the relational database PodVod (an acronym for groundwater).

The necessity of creating a centralized borehole database arose from the growing demand on quality hydrogeological data, especially due to increased usage of digital technologies, such as geographic information systems (GIS) and web-based solutions. Its importance is undisputable, since having all hydrogeological data stored in one place, in uniform structure and accessible by several means has benefits in speed of information retrieval, interoperability and elimination of duplicate work. Furthermore, it makes possible to analyse large number of boreholes at once, covering large areas, and thus allowing for regional or even national studies to be performed more efficiently, and revealing other important, otherwise hidden, "data behind data". Another motivation in creating the common database was to re-evaluate hydraulic tests made at boreholes by using same methodology, making the values of hydraulic parameters more comparable. For this sake a computational module was developed and integrated into the database application, which calculates transmissivity and permeability of an aquifer based on pumping test data (drawdown vs. yield), described in chapter 3.3. A team of hydrogeologists had been checking the data for errors, adding new data and re-evaluating all well tests within the framework of the research project named "Integrated Landscape Management" (Malík et al., 2007).

3.2.1 Database concept

Taking into account the character of available source data, approximate size of datasets, hierarchical nature of the data and other factors like need of complex queries and relative ease of implementation, a relational database model was adopted as fitting the best to our requirements. In this concept data are stored in interconnected tables containing logically and thematically grouped items, in which one row represents a single piece of information – a record, comprising several attributes in dedicated fields. Tables are related based on common index fields. To ensure that only valid data are entered in some fields or to eliminate inserting indiscriminate and fuzzy values, main tables containing thematic data are accompanied by several lookup tables, holding enumerative items and predefined lists to choose from.

The core structure of the database conforms to the entries in the borehole register cards, partly preserved also in the original dBase archive. Certain parts of the database were added to maintain continuity with existing well tests data, stored in separate datasets for different regions

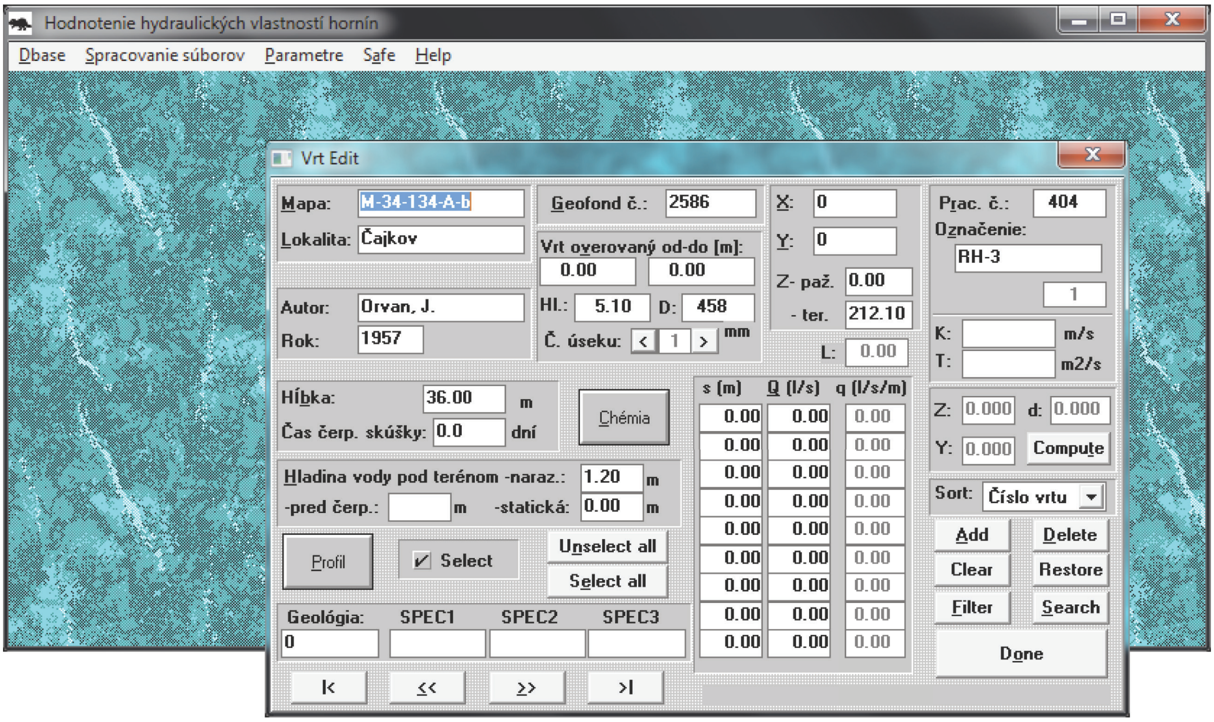


Fig. 3.3 User interface of HydroSis program.

of Slovakia, which had been processed within the custom HydroSis software, which is in possession of the Department of Hydrogeology and Geothermal Energy of SGIDŠ (Fig. 3.3). For this purpose special procedures were developed to streamline the import process.

3.2.2 Database design

After the main concept of the database was accepted, a decision had to be made in regard to the technical implementation. The key considered factors were data security and integrity, adaptability, number of concurrent users, easy deployment as well as user friendliness and versatility. All these criteria and technical constrains are fulfilled by the platform of Microsoft® Access database. With relatively little effort a powerful and reliable database could be set up, with user interface that most of the users are already familiar with. Moreover, the database does not require a database server and the *.mdb* format is widely supported. If no advanced functionality is needed, just the free Microsoft Access Runtime is required to work with the data. The database references Microsoft Data Access Objects (DAO) and ActiveX Data Objects libraries.

The database was structured as a two-compound system, consisting of the so-called back-end, containing solely the data, and the front-end, with user interface and application extension. Both front-end and back-end files together with the workgroup security file (*.mdw*) are hosted on a Samba share of the Department's file server within a local area network (LAN), which is accessible by all authorised users. The number of concurrent users that can simultaneously access and edit the data, is practically unlimited. Parallel editing, inserting and deleting of data is ensured by the engine of Microsoft Access itself, with locking at record level and providing conflict handling and resolution. Furthermore, other clients like different databases or GIS can also have a read/write access to the database by means of ODBC connectivity.

Following are the main tables constituting the back-end database:

Table name	Content
VRT	Pivot table, contains basic identification and description of boreholes;
SPEC_VRT	Complementary information on boreholes (specifics);
SPEC	Borehole specifics look-up table;
PROFIL	Interpreted geological borehole profiles;
HORNINY	Rock types look-up table;
VRTANIE	Depths and diameters of the well bore;
PAZENIE	Depths and diameters of well casings;
FILTER	Depths of screened intervals of wells (filters, perforated screens) in boreholes;
CERP_SK	Basic information on well tests;
CERP_SK_STUPNE	Measured well yields and drawdowns during well tests;
POP_GEOFOND	Geological profiles of boreholes;
CHEMIA	Basic information about chemical analyses of water;
CHEMIA_HODNOTY	Measured values of components from water analyses;
CHEMIA_PRVKY	Water analysis components look-up table;
GEOL_KOD	Basic stratigraphic indexes of boreholes look-up table;
GEO_LEG	Unified geological legend;
GEOL_LEG_IMK	Unified hydrogeological legend;
GEOL_ID_LITO	Lithology look-up table;
GEOL_ID_GEN	Sediment's depositional environment look-up table.

The tables are related to each other by specifying index fields as primary and foreign keys, as can be seen on Fig. 3.4. The type of field relations can either be one-to-many (1:∞), many-to-one (∞:1) or undefined (∞:∞). Referential integrity is enforced, meaning that related child records are being automatically cascade updated or deleted upon change in the parent. Orphaned records are thus supressed.

Tables have defined very efficient structure with carefully chosen field types and sizes. Only prescribed values or certain range of values are permitted in some of the fields, which is in most cases defined directly in tables design. In some cases users are warned by the graphical interface when trying to enter inconsistent values, for example groundwater table deeper than the drilled depth.

3.2.3 User interface and functionality

Graphical user interface offers a convenient means to access the underlying data, enables easy navigation through records, visually groups related parts of the database, visualizes boreholes on an integrated map and provides extended functionalities. It is made up from different forms, each dedicated to a specific use. The interface is complemented by a comprehensive user help, every part of all the forms is described in small popping-up windows for better understanding of the contents.

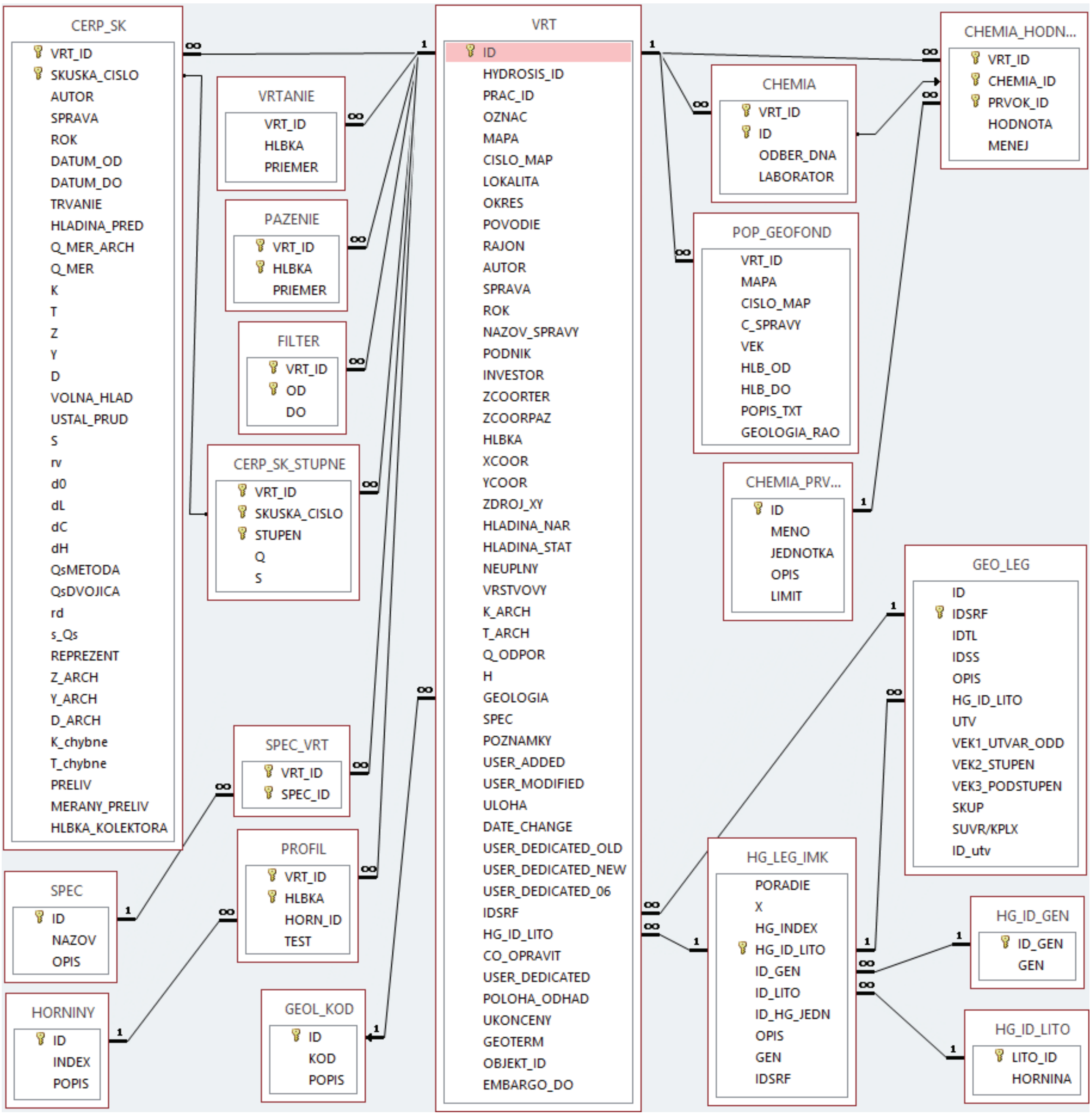


Fig. 3.4 Schematic diagram of the database structure, showing tables and their relations.

After starting the database an initial dialog appears (Fig. 3.5), letting the user choose from five possible actions:

1. Open the borehole database (button “Vrty”);
2. Synchronize database replicas (button “*Synchro*”, now inactive);
3. List of possible erroneous or illogical data(button “*Chyby*”);
4. Backup the database (button “*Zálohuj*”);
5. Close the database and end the work (button “*Zavri*”).

Main form

By pressing the “Vrty” button, the main form opens (Fig. 3.6).

This form has five main sections. In the top row seven functional buttons are placed, having different purpose. First button is a toggle that opens a map window, which will be discussed later. Second and third buttons serve for dealing with duplicate records. Button № 4 enables to open a pre-saved SQL query, which allows to work on only a subset of boreholes for different purposes. Pressing this button opens a list of available queries to be selected from (Fig. 3.7).

The sixth button sorts the boreholes by the date of the last change (this is useful when aiming to quickly locate the borehole that the user last worked at) and button № 7 exports the currently selected boreholes with corresponding data to a formatted Excel spreadsheet for publication purposes.

Six large buttons in the bottom row of the form work as toggles for opening and closing different auxiliary forms, from left to right they are:

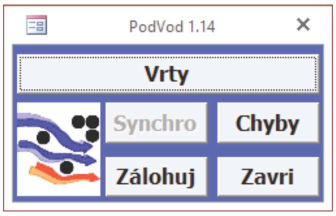


Fig. 3.5 Start-up dialog.

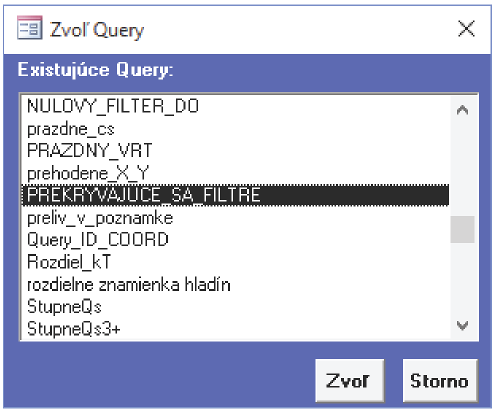


Fig. 3.7 Select query dialog.

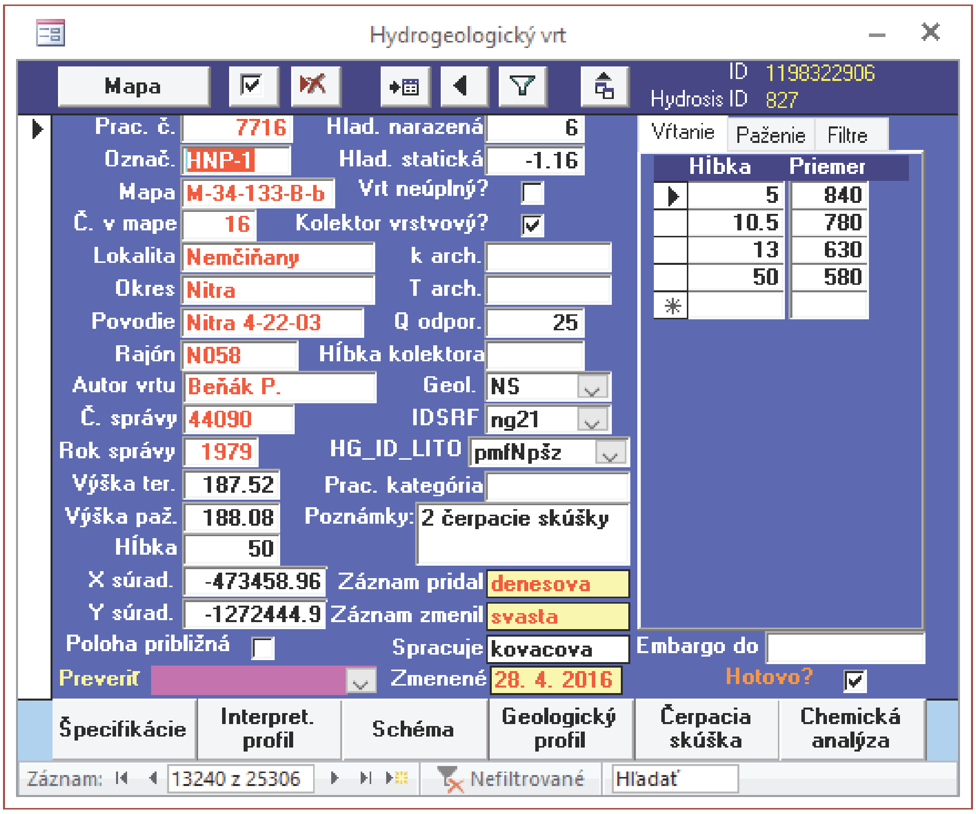


Fig. 3.6 Main form.

1. Specifications;
2. Interpreted geological profile;
3. Borehole schematic diagram;
4. Complete geological profile;
5. Pumping tests;
6. Chemical analyses.

These forms can be switched on and off and placed around the computer screen, depending on current user's needs (Fig. 3.8). The layout of the user's workspace is preserved. When browsing through borehole records, data in all open auxiliary forms are updated automatically to reflect the currently displayed borehole.

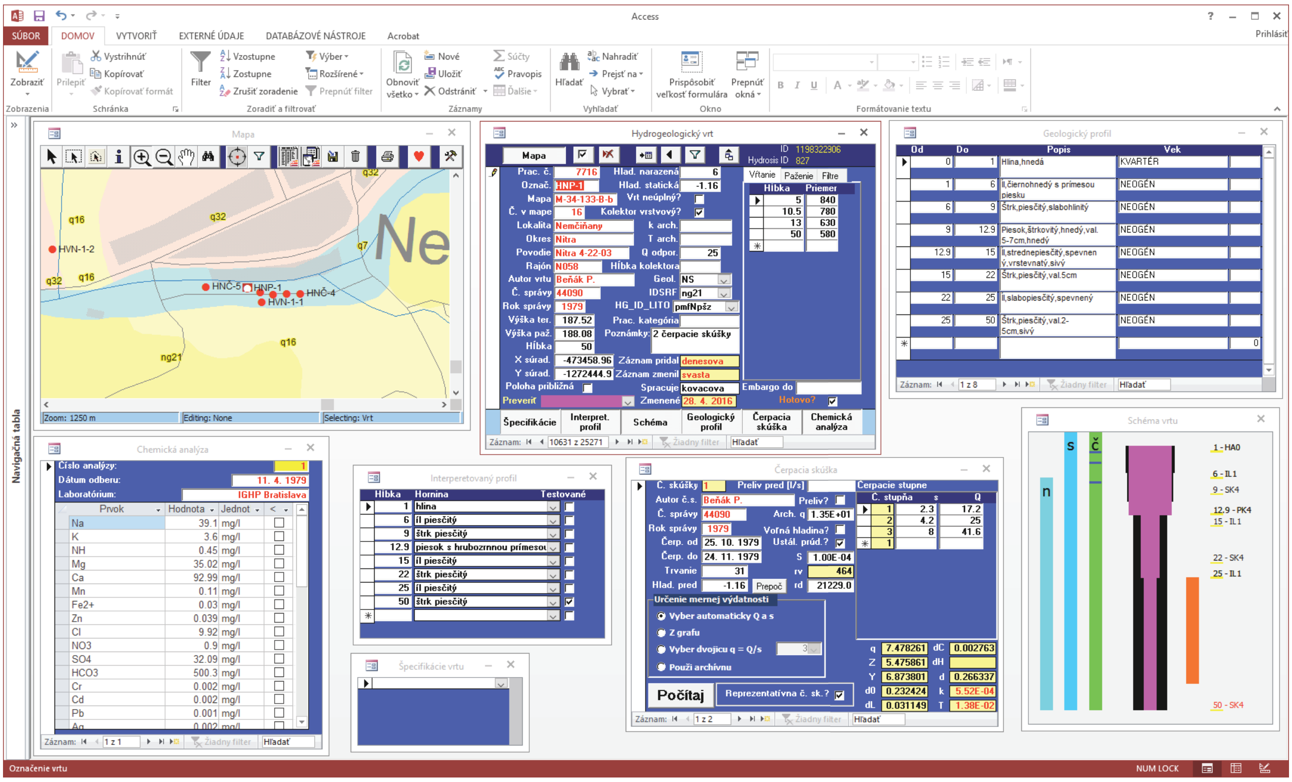


Fig. 3.8 Example of organizing forms in a user workspace.

On the right side of the main form (Fig. 3.6) three sub-forms with data arrays are placed, containing information on the construction of the borehole (Fig. 3.9). Individual data arrays are accessible by clicking on respective flaps. The first one contains diameters [mm] and corresponding measured depths [m] of the drilling. Diameters [mm] and measured depths [m] of the borehole casings are on the second sub-form. The last array contains measured depths [m] of top and bottom of screened parts of the well.

Fig. 3.9 Borehole construction data arrays.

The central part of the main form holds the basic information related to the selected borehole. It contains the following fields:

- Different IDs;
- Borehole label;
- Map sheet and number;
- Locality;
- District;
- Watershed;
- Hydrogeological region;
- Author of borehole, report № & year of publishing;
- Altitude of the ground;

- Altitude of measuring point (usually top of casing);
- Measured depth of borehole;
- X and Y coordinates (in Krovak's geographic projection);
- Depth of water table (first appearance & static);
- Relative position of borehole to aquifer;
- Type of aquifer;
- Archived values of aquifer's permeability and transmissivity;
- Recommended maximum pumping rate;
- Depth of aquifer (if known);
- Main geological classification, detailed stratigraphical and lithological description (Fig. 3.10) and hydrostratigraphic index of aquifer;
- Supplementary information and notes;
- Name of the user who added and last edited the data, plus the date of last change.

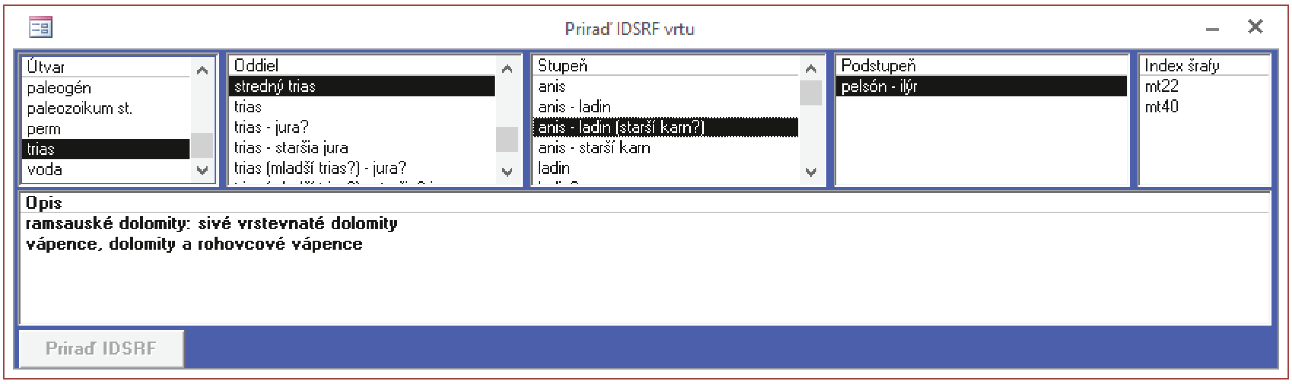


Fig. 3.10 Tool for stratigraphical and lithological characterisation of an aquifer.

Interactive map

Because currently 24,070 out of 25,323 hydrogeological boreholes in the database are accompanied by their geographic coordinates, they can be displayed on a map, too (Fig. 3.11). This is very useful while working on regional hydrogeological problems, when nearby boreholes can be easily found. Different thematic layers such as geology or topography can be underlain, giving a better overview on borehole's surroundings. For this task a MapInfo Professional™ desktop GIS was used to provide mapping functionality in Access database. The smooth integration of MapInfo in Access form is via Microsoft's OLE (Object Linking and Embedding) technology. The result is almost a fully functional MapInfo map inside Access form, closely linked to the data in the database.

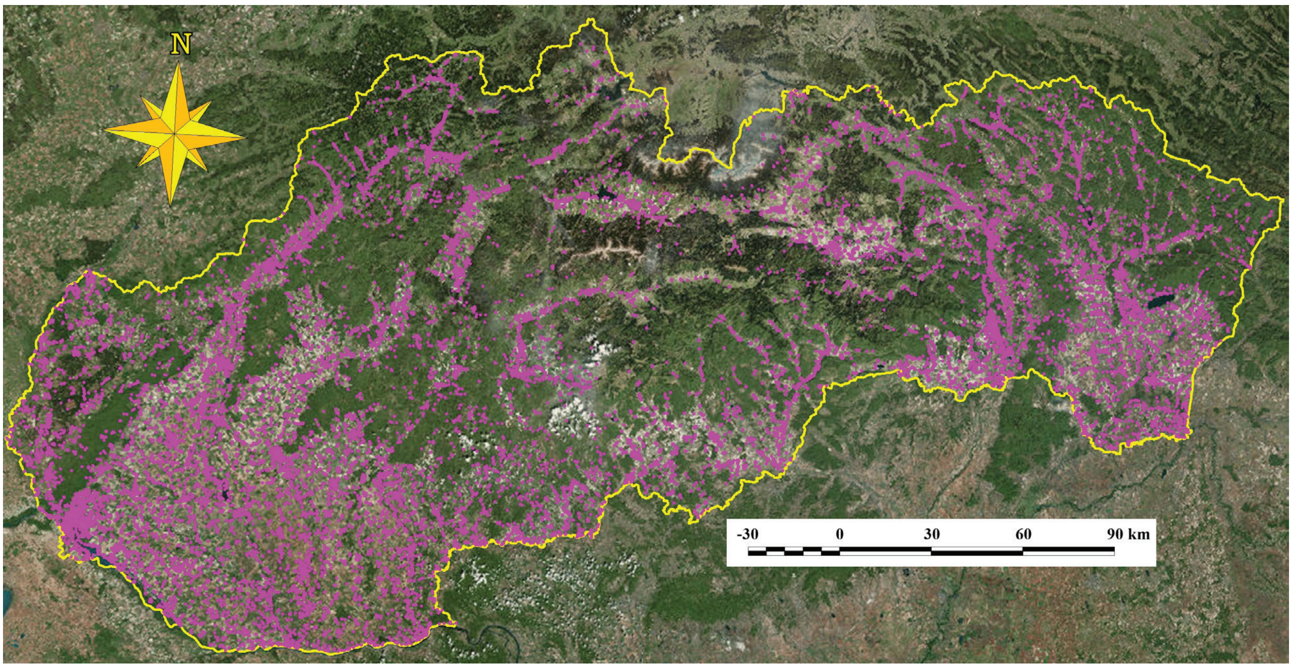


Fig. 3.11 Spatial distribution of 24,070 hydrogeological boreholes (violet dots) in Slovakia. Topography © ArcGIS World Imagery contributors.

The interactive map form contains the map window and a set of functional buttons on the top (Fig. 3.12). The buttons have the following functions (from left to right):

- Select objects one by one;
- Select objects within a rectangle;
- Select objects within a polygon;
- Give information on object;
- Zoom in;
- Zoom out;
- Pan view;
- Find borehole in the database;
- Localize current borehole on a map;
- Filter selected boreholes;
- Add new map layer;
- Open a saved map composition;
- Save current map composition;
- Remove map layers;
- Print map;
- Refresh borehole map;
- Run MapBasic® command.

Other functionalities, like changing a view or reorganizing map layers, are accessible from a context menu by right-clicking into the map window.

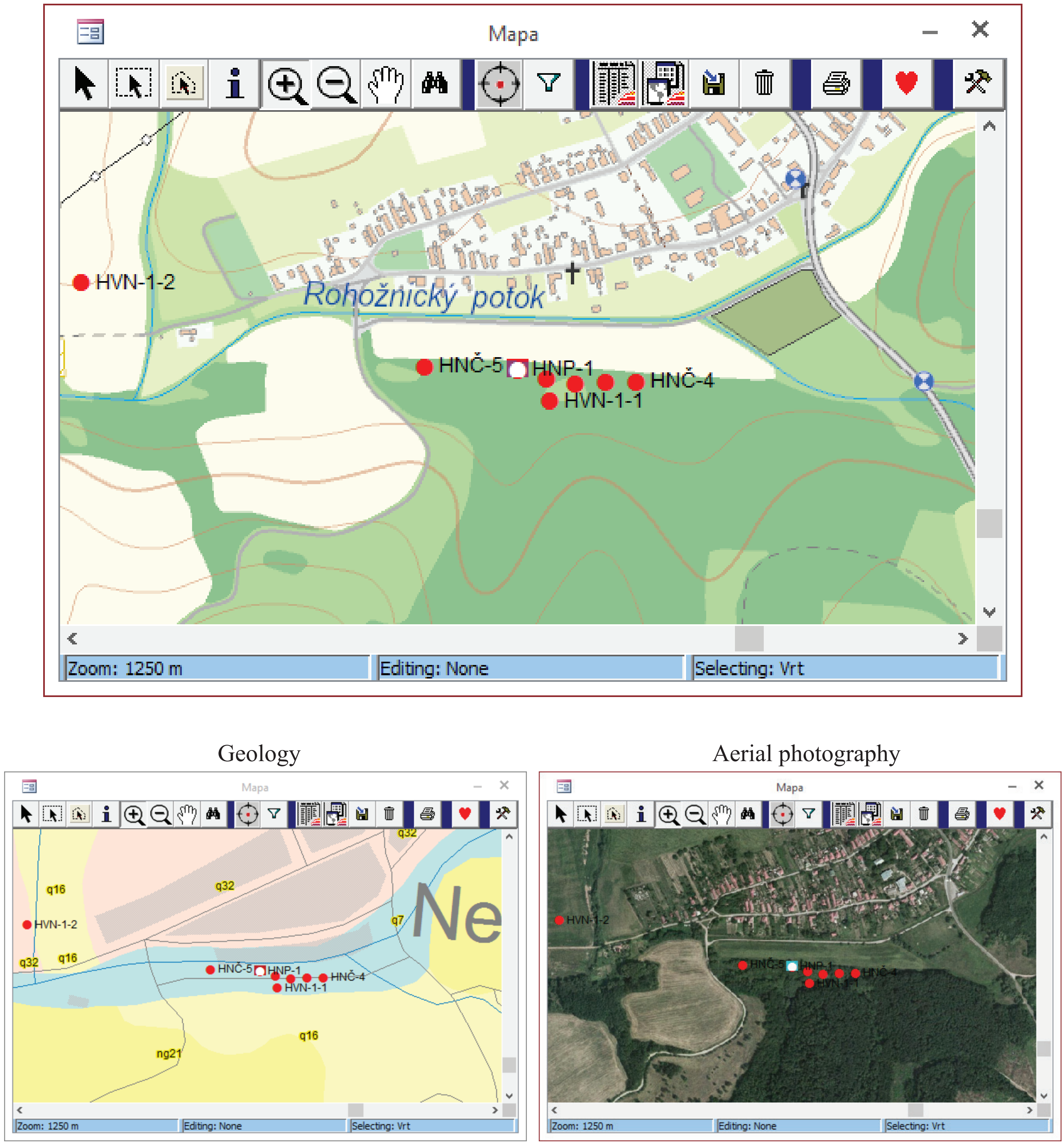
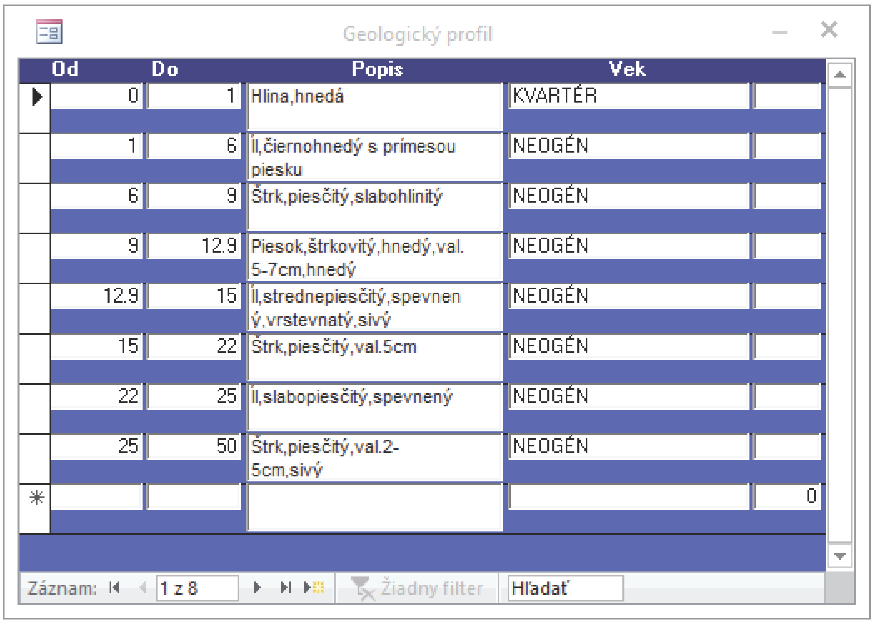


Fig. 3.12 Interactive map with boreholes (red) and different backgrounds (© Geological map of the Slovak Republic at 1:50,000, ZBGIS® - Institute of Geodesy and Cartography Bratislava, National Forest Centre Zvolen).

Geology

During a borehole drilling all rock types found are recorded together with respective measured depths. In most cases, the rocks are primarily classified into basic stratigraphic units. Since this is primary geological information, it is exactly preserved in the database (Fig. 3.13).

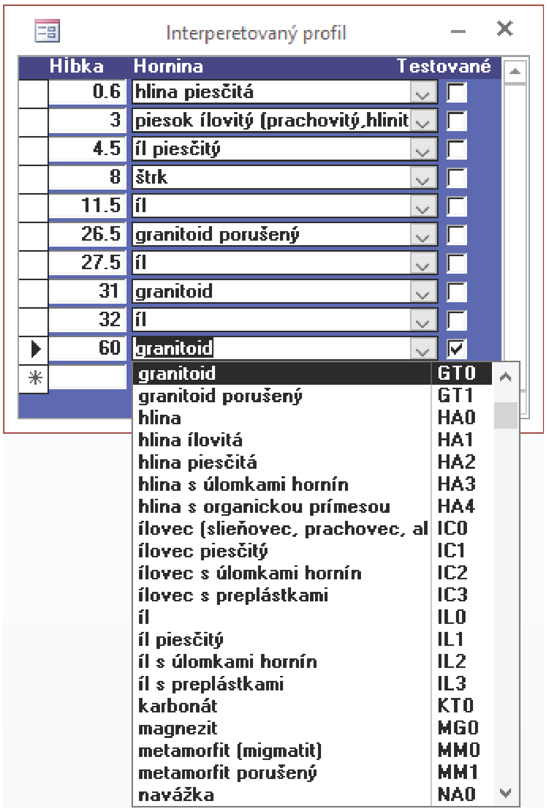

Geologický profil

Od	Do	Popis	Vek	
0	1	Hlina,hnedá	KVARTÉR	
1	6	Il,čiernohnedý s prímesou piesku	NEOGÉN	
6	9	Štrk,piesčitý,slabohlinitý	NEOGÉN	
9	12.9	Piesok,štrkovitý,hnedý,val. 5-7cm,hnedý	NEOGÉN	
12.9	15	Il,strednepiesčitý,spevnený,vrstevnatý,sivý	NEOGÉN	
15	22	Štrk,piesčitý,val.5cm	NEOGÉN	
22	25	Il,slabopiesčitý,spevnený	NEOGÉN	
25	50	Štrk,piesčitý,val.2-5cm,sivý	NEOGÉN	
				0

Záznam: 1 z 8 Žiadny filter Hľadať

Fig. 3.13 Detailed geological profile form.

Because the detailed geological description is stored as a free text, it is not possible to process it later. Therefore a big effort of a large interpretation team of hydrogeologists was made to group and classify these lithological descriptions into 69 hydrogeologically important rock types (Fig. 3.14). Besides this, rock "layers" that were identified as part of an aquifer and affected by the pumping test, were also marked. Now such processed hydrogeological profiles are easy to be queried, statistically processed and transferred to other data formats for later use, e.g. in groundwater modelling.


Interperetovaný profil

Hĺbka	Hornina	Testované
0.6	hlina piesčitá	☐
3	piesok ílovitý (prachovitý,hlinit	☐
4.5	íl piesčitý	☐
8	štrk	☐
11.5	íl	☐
26.5	granitoid porušený	☐
27.5	íl	☐
31	granitoid	☐
32	íl	☐
60	granitoid	☑

granitoid	GT0
granitoid porušený	GT1
hlina	HA0
hlina ílovitá	HA1
hlina piesčitá	HA2
hlina s úlomkami hornín	HA3
hlina s organickou prímesou	HA4
ílovec (slieňovec, prachovec, al	IC0
ílovec piesčitý	IC1
ílovec s úlomkami hornín	IC2
ílovec s preplástkami	IC3
íl	IL0
íl piesčitý	IL1
íl s úlomkami hornín	IL2
íl s preplástkami	IL3
karbonát	KT0
magnezit	MG0
metamorfit (migmatit)	MM0
metamorfit porušený	MM1
navážka	NA0

Fig. 3.14 Interpreted lithological profile form.

Interpreted lithological profile, together with borehole's construction and information on groundwater levels can be visualized on a single scheme by pressing the "Scheme" button, as seen on Fig. 3.15.

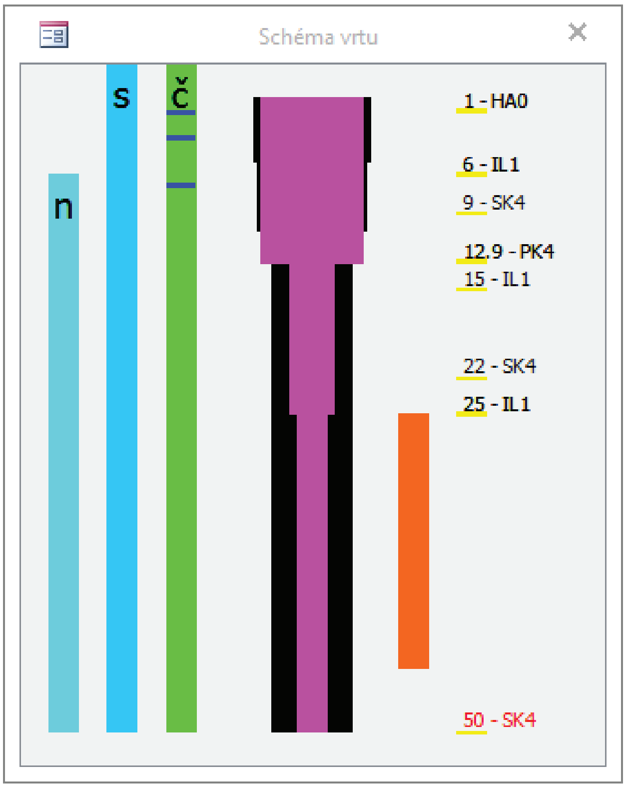


Fig. 3.15 Hydrogeological borehole schematic diagram.

Chemical analyses

In well drilling projects aimed on finding new water sources the groundwater quality is of concern, therefore chemical analyses of water were made and archived in reports. Because the water chemistry data in reports are often in different units, a unified list of 140 chemical elements/compounds/indicators and physical quantities had to be made first. In our database water chemistry data is handled by three interconnected tables, accessible together in one user form (Fig. 3.16).

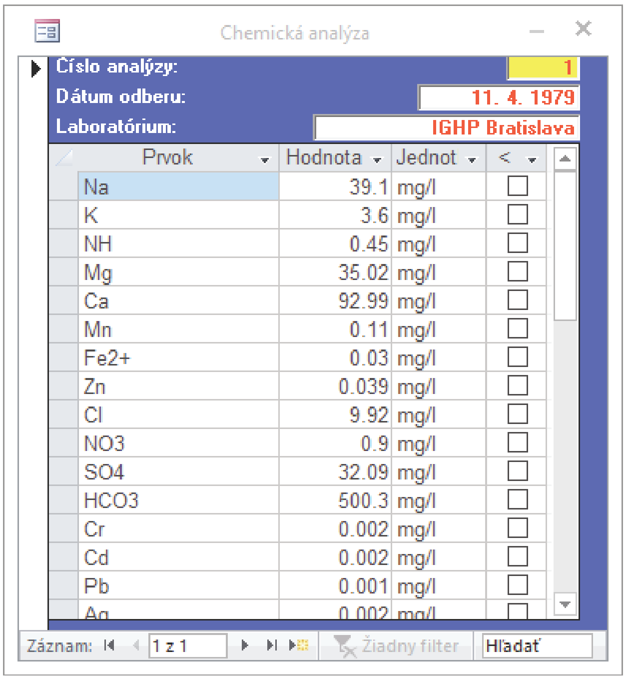


Fig. 3.16 Chemical analysis form.

Pumping tests evaluation

Typical hydrogeological borehole has at least one short-term pumping test made, resulting in basic hydraulic parameters estimation. These data are the most valuable, since they indicate an aquifer's characteristics from transmissivity and storage perspective. Also important is that pumping tests allow for evaluation of total utilized water withdrawn from an aquifer and so helping in groundwater reserves calculation. However, these tests were made by many authors using different methodologies, yielding parameters of different quality. To make these data comparable a re-evaluation of all pumping tests by a common method was necessary. The pumping test form provides means not only to view, add or edit well test data, but also to calculate comparative hydraulic parameters out of it, using methodology of Jetel (1964, 1985, 1995a, 1995b) and Jetel & Krásný (1968). This is in detail described in Chapter 3.3.

The pumping test form (Fig. 3.17), designed for this purpose contains all necessary data of all pumping tests made on a particular borehole plus a VBA code for calculating hydraulic parameters. In the top-left part of the form a user adds the following information:

- Author, number and year of the report on the pumping test;
- Date and time of the test start and the end;
- Duration of test;
- Water level before the test start;
- Overflow (if exists);
- Estimate of storativity of an aquifer;
- Estimate of depression cone radius.

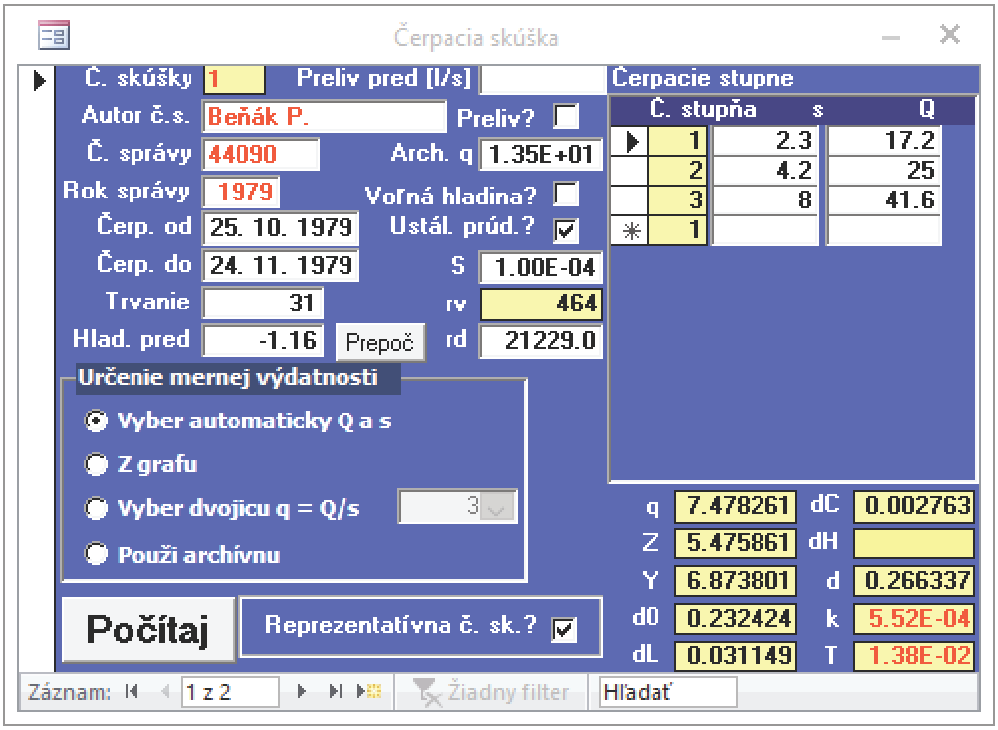


Fig. 3.17 Pumping test form layout.

In a top-right array pairs of steady state drawdown and yield values are added. The rest of the necessary data, such as layer thickness and total length of screened intervals is derived from values already inserted in other parts of the database. If all data are present, a user chooses the method of specific yield calculation. Four options are available: let the program calculate it automatically; calculate it from linear regression; select the most representative pair of ***Q*** and s values or use an archive value of specific yield. In case of linear regression, a user is assisted with a chart (Fig. 3.18).

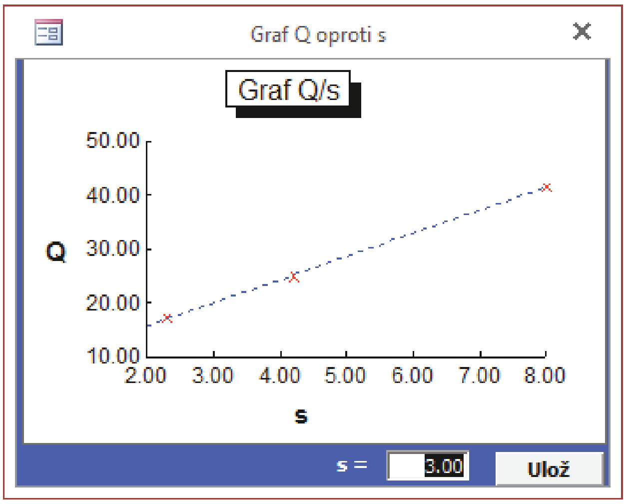


*Fig. 3.18 Well yield (**Q**) vs. drawdown (**s**) relationship chart.*

After that the calculation is performed by pressing the button. The program first cross-checks all data requirements and in some cases recommends change in some parameters or asks for additional information. Finally the values of rock permeability and aquifer transmissivity are calculated and inserted into the database (red text boxes in the lower-right corner of the form).

3.3 BOREHOLE PUMPING TESTS REINTERPRETATION PRINCIPLES

Rock-mass hydraulic properties are the key factor in controlling groundwater flow and thus are interesting from the points of view of groundwater supply and protection of groundwater resources. The vast majority of pumping and recovery tests on wells are performed without recording the data from observation boreholes – piezometers, what encounters for the necessity of using groundwater table data from the pumped well only. In such a case, plenty of specific aspects arise during the assessment of hydraulic parameters. Estimation of transmissivity ***T*** from specific capacity (***Q***/***s***; discharge vs. drawdown ratio) in these cases can serve as relatively easy tool of acquiring information on hydraulic aquifer properties. Such an approach was discussed mostly for porous aquifer media (starting from e.g., Thomasson et al. 1960; Theis 1963; Jetel 1964, 1985), but some authors have also dealt with similar techniques applied for fractured or karst rocks (El-Naqua 1994; Mace 1997; Verbovšek 2008; Malík & Švasta 2010; Malík et al. 2015). El-Naqua (1994) used the empirical correlation of 237 transmissivity/specific capacity pairs in fractured carbonate aquifer, while Hamm et al. (2005) performed a similar correlation of 117 time-drawdown datasets from 116 wells in a volcanic aquifer. Mace (1997) examined the uncertainty in well loss estimates (from pipe-flow theory) to link with specific capacity, influenced by well loss, and transmissivity of karst aquifer. The resulting empirical relation was different from such relations in other aquifer types and pointed out the potential errors in well loss estimates. Mabee (1999), Henrikssen (2003), Razack & Lasm (2006), or Verbovšek & Veselič (2008) tried to geostatistically correlate factors as depth to the water table, overburden properties, overburden thickness, precipitation, net precipitation, runoff, regional stress fields, geomorphological position or proximity to rivers with well yields, specific capacities or transmissivities in igneous and metamorphic rocks or dolomites. Regional stress fields, fault zones or geomorphology were factors considered to influence regional hydraulic properties of rocks. Razack & Lasm (2006) also found a significant statistical relationship between transmissivity and the specific capacity in a fractured hard rock aquifer using data from 118 measured data points. Verbovšek (2008) correlated ***T*** and specific capacity from 298 wells in dolomitic aquifers, showing that in these rock media the T-***Q***/***s*** correlation coefficient does not increase with logarithmic transformation of the data.

Calculation of "logarithmical conversion differences", parameters concerning hydraulic resistivities of both wells and aquifers (Jetel 1964, 1985, 1995a, 1995b, Jetel & Krásný 1968) enabled the use of unified "standard" specific capacity data to eliminate influences of differently performed pumping tests. As the drawdown data acquired at the pumped well cannot be used in any of equations in which drawdown value ***s*** is expressed as a function of distance ***r*** from the borehole axis or time value ***t*** in a direct form, as already in steady flow conditions, flow field in the close vicinity of a well and on a well wall is deformed, due to the resistance of the near-wall zone (skin effect), which can be accompanied, in case of unconfined water table, by outseepage offset of groundwater table. In transient flow, these unfavourable effects are contributed by volume storage effects. The storage effect is especially pronounced when low transmissivity aquifer is tested by a relatively short test on a large–diameter well.

It is practically impossible to assess values of capacity parameters (storativity ***S***, specific storativity S_s), neither resistance-capacity parameters (hydraulic diffusivity) without data from observation boreholes. Without these data, it is also not possible to give clear quantitative characteristics of boundary conditions as distance to lateral boundary or leakage parameters.

Hydraulic tests from which the only data are acquired directly in the pumped well, are available, thus provide only a limited set of information about aquifer hydraulic parameters and about boundary conditions. Still, these data allow us a direct assessment of resistance hydraulic parameters (transmissivity ***T***, hydraulic conductivity ***K***, in the absolute system also intrinsic permeability *κ* and coefficient of intrinsic transmissivity T_a) and, under a certain circumstances, also quantitative characteristics (determination of type) of boundary conditions.

Archive files of common well / hydrogeological boreholes, which are usually stored, contain also precious information about the tested aquifer, which can be thoroughly disclosed by the used of appropriately chosen algorithm. Although many times only data on pumped discharge, drawdown of water level in a well, well diameter and levels of open casing remain (together with some records about aquifer position), these can help us to interpret basic knowledge on aquifer hydraulic properties. Taking into account the quality of available data, we use calculation of usual hydraulic parameters of rock environment (hydraulic conductivity ***K***, transmissivity ***T***) by help of comparative parameters (transmissivity index ***Y***, permeability index ***Z***) which, in general, represent negative logarithmic derivations of transmissivity and hydraulic conductivity values. In some cases, one can also use both ***Y*** and ***Z*** indexes in order to show basic classification of permeable environment into classes from 1 to 10. Such an idea of substitution of physically defined hydraulic parameters by some comparative semi–quantitative parameters is relatively old (e.g. Jetel & Krásný, 1968, Jetel, 1989, Šarin, 1990). Also here, transmissivity index ***Y*** and permeability index ***Z*** are referred to as approximate logarithmical parameters. Although derived only from specific yield values, they can serve as a good indicator of aquifer's hydraulic properties. But, as a substitution for specific capacity, they will serve us in further calculation of hydraulic conductivity ***K*** and transmissivity ***T*** estimates.

Definitions of permeability index Z and transmissivity index Y

The comparative parameter of transmissivity, derived from specific capacity of a well, is the transmissivity index ***Y*** (Jetel & Krásný 1968), which is derived from specific capacity (at unit drawdown of 1 m, see also the text below) ^1q after equation (1):

$$Y = \log (10^6 q^1) = 6 + \log {}^1q \qquad (1)$$

The comparative parameter of hydraulic conductivity, derived from specific capacity, is the permeability index ***Z*** (Jetel 1964), which is also derived from specific capacity ^1q after equation (2):

$$Z = \log 10^6 ({}^1q / M) = 6 + \log ({}^1q / M) \qquad (2)$$

where:
M – aquifer thickness [m]
^1q – standard specific capacity = specific capacity at unit drawdown [$l \cdot s^{-1} \cdot m^{-1}$]

In this paper, comparative hydraulic indexes substitute specific yield and are used for further transformation into transmissivity and hydraulic conductivity by means of "conversion difference". One should note that comparative indexes are derived from discharge data in [$l \cdot s^{-1}$]. When entering discharge in SI units [$m^3 \cdot s^{-1}$], exponents of "9" value should be introduced instead of "6" into equations (1) and (2). To enable better direct comparison of real transmissivity values ***T*** and the comparative indexes ***Y***, logarithmical transformation of transmissivity Y_T – for discharge data in [$l \cdot s^{-1}$] – can be defined using equation (3). The same can be done for hydraulic conductivity ***K*** and permeability index ***Z***, resulting in Z_k after equation (4):

$$Y_T = \log T + 9 \qquad (3)$$

$$Z_k = \log K + 9 \qquad (4)$$

Calculation of standard specific capacity

During evaluation of a pumping test, that provided only discharge and drawdown data on the tested borehole, comparative parameter values – permeability index ***Z*** and transmissivity index ***Y*** are basically derived from **specific capacity**, expressed as a ratio between discharge ***Q*** and corresponding drawdown ***s*** in the well, using equation (5).

$$q = Q / s \qquad (5)$$

where:
q – specific capacity [$l \cdot s^{-1} \cdot m^{-1}$]
Q – (pumped) discharge [$l \cdot s^{-1}$]
s – groundwater table drawdown in a well [m]

To derive the representative comparative indexes, discharge under the same (relatively low) drawdown conditions should be chosen. With respect to generally nonlinear dependency of ***Q*** on ***s***, it is recommended to use the unified value of discharge – e.g. at the first meter of drawdown (i.e. $s = 1$ m $= {}^1s$) in the equation (5) when possible, or to substitute the measured one (pumped under the real circumstances) by a recalculated value. In this case, unit drawdown specific capacity ^1q = "standard specific capacity" as defined by Jetel (1985, 1995a), stands for specific capacity. When measured drawdown values ^ns differ from 1 m, in the case of thick (M > 10 m) unconfined aquifer, specific capacity at unit drawdown will be calculated with equation (6):

$$^1q = {}^nq \cdot (2 \cdot M - 1) / (2 \cdot M - {}^ns) \qquad (6)$$

where:
^1q – standard specific capacity = specific capacity at unit drawdown [$l \cdot s^{-1} \cdot m^{-1}$]
^ns – unconfined groundwater table drawdown, measured in a well [m]
M – original thickness of an unconfined aquifer unaffected by pumping [m]
^nq – specific capacity at drawdown ^ns [$l \cdot s^{-1} \cdot m^{-1}$]

If, while performing an unconfined aquifer test, the drawdown exceeds value more than 1/10 of the original aquifer thickness ***M***, the measured drawdown should be adjusted after equation (7) (Jacob 1944, in Jetel 1985) and an adjusted drawdown s_c (8) should be used instead of measured drawdown ***s*** in specific capacity calculations. Such an adjustment is necessary due to significant reduction of the groundwater flow cross-sectional area and thus lowering of transmissivity, too.

$$s_c = {}^n s - s^2 / (2 \cdot M) \qquad (7)$$

where:
s_c – adjusted unconfined groundwater table drawdown in a well [m]

$$ {}^1 q = Q / s_c \qquad (8)$$

In the case when standard specific discharge calculation was performed without drawdown adjustment (***s*** to s_c), in spite of the fact that the drawdown in the well exceeded 1/10 of the unaffected unconfined aquifer thickness, in the sense of equation (7) the value of the adjusted standard specific discharge ${}^1 q_c$ should be used to calculate values of approximate logarithmical parameters ***Y*** and ***Z***. Value of ${}^1 q_c$ is obtained according to the equation (9):

$$ {}^1 q_c = {}^1 q \cdot (2 \cdot M) / (2 \cdot M - 1) \qquad (9)$$

where:
${}^1 q_c$ – adjusted standard specific capacity [$l \cdot s^{-1} \cdot m^{-1}$]

In the process of permeability index ***Z*** calculation (eq. 2) instead of drawdown adjustment or using adjusted standard specific capacity, value of adjusted aquifer thickness M_c, derived from original thickness ***M***, can be used. For calculation of adjusted aquifer thickness ***Mc***, equation (10) can be employed. One can use the M_c value in equation (2), but in the same time, an unadjusted value of standard specific capacity ${}^1 q$ should be used.

$$M_c = M - {}^n s / 2 \qquad (10)$$

where:
M_c – adjusted thickness of an unconfined aquifer [m]

Under confined aquifer conditions, the dependency of discharge ***Q*** from drawdown ***s*** is less or more linear up to a certain threshold value of ***s***. For higher piezometric depressions, however, this relation becomes non-linear. If there are enough pairs of both ***Q*** and ***s*** values for identification of ***Q***=f(***s***) curve, the standard specific capacity can be derived graphically by interpolation or extrapolation to ***s*** = 1 m value. If we do not have this possibility, an estimation of standard specific capacity can be performed using relation shown in eq. (6) in parabolic approximation of the curve (equation 11):

$$ {}^1 q = {}^n q \cdot (2 \cdot H - 1) / (2 \cdot H - {}^n s) \qquad (11)$$

where:
H – distance between the static water level in a well and lowest part of the open well casing [m]

In this manner, unification of data from different wells with different drawdowns and discharges can be achieved. Even though the aforementioned procedure is only a rough approximation of an unknown nonlinear curve ***Q***=f(***s***), it allows for objectively reproducible correction of the specific capacity decrease with drawdown to achieve their comparability. In our borehole dataset, analysed for 16,729 hydrogeological wells and boreholes, average value of transmissivity index ***Y*** was 5.90, with median of 5.99 and standard deviation 0.98. Upper and lower 10% percentile values were within the interval of <4.57; 7.09>, while minimum ***Y*** values of 1.49 and maximum of 9.85 were found. The permeability index, ***Z***, reached the values from -0.48 to 8.56 (minimum and maximum), while average value of 4.95, median 5.16 and standard deviation 1.18 were found. Upper and lower 10% percentile limits for permeability index ***Z*** were 3.29 and 6.30.

Logarithmic conversion difference principle

Because the comparative parameters ***Z*** and ***Y*** represent individual functions of specific capacity ***q*** values, the estimation of hydraulic parameters of rocks from approximate (comparative) parameters originates from the existence of the relation between transmissivity coefficient ***T*** and specific capacity ***q***, which is, for our purpose, expressed in a form of a logarithmic conversion difference, defined by Jetel (1985) in equation (12):

$$d = \log T - \log q \qquad (12)$$

i.e.

$$T / q = 10^d \qquad (13)$$

where ***T*** and ***q*** are expressed in [$m^2 \cdot s^{-1}$]. From comparison of (12) and (13) it is clear that, that the relation between transmissivity coefficient ***T*** and transmissivity index ***Y*** as a transformation of specific capacity ***q*** can be expressed by equation (14):

$$T = \text{antilog}\,(Y + d - 9) = 10^{(Y + d - 9)} \qquad (14)$$

The same applies for the relation of hydraulic conductivity ***K*** to permeability index ***Z***, where:

$$K = \text{antilog}\,(Z + d - 9) = 10^{(Z + d - 9)} \qquad (15)$$

where:
T – aquifer transmissivity [$m^2 \cdot s^{-1}$]
K – aquifer hydraulic conductivity [$m \cdot s^{-1}$].

Logarithmic implication of equations (12) and (13) is the expression of logarithmic conversion difference as a difference between values Y_T and ***Y***, after introduction of transformation of Y_T defined by equation (3), i.e. as:

$$d = Y_T - Y \qquad (16)$$

By introducing the conversion difference, the whole problem of estimation of hydraulic conductivity ***K*** from transmissivity index ***Y*** is simplified into a problem of optimal estimation of the corresponding conversion difference ***d***. The conversion difference is composed by primary conversion difference d_0 and additional difference d_d (17):

$$d = d_0 + d_d \qquad (17)$$

In other words, logarithmic conversion difference ***d*** contains the key for calculation of hydraulic parameters from simple value specific capacity, as by the use of eq. (14) and (1), if Q/s is the standard specific capacity, e.g. transmissivity equals to $10^{log(Q/s) + d - 3}$.

Estimation of conductivity (resistance) hydraulic parameters using logarithmic conversion difference

Primary conversion difference

The basic constituent of the total conversion difference $\boldsymbol{d}$ in equations (14) and (15) is a conversion difference expressing the difference between log $\boldsymbol{T}$ and log $\boldsymbol{q}$ for given calculation conditions, assuming a hydrodynamically perfect well – i.e. a well, of which radius $\boldsymbol{r_v}$ equals the effective (equivalent) radius $\boldsymbol{r_{ev}}$, or by other words – a well without additional hydraulic resistance of flow into the well and inside the well towards the well head. This component, i.e. the ideal value of the conversion difference $\boldsymbol{d}$ for hydrodynamically perfect well, is denoted as primary conversion difference $\boldsymbol{d_0}$ (dimensionless). Jetel (1985) derived the value of the primary conversion difference $\boldsymbol{d_0}$ within the conditions of validity of the Dupuit–Thiem equation (steady radial flow to a hydrodynamically perfect well) which is then expressed by the equation (18):

$$\boldsymbol{d_0 = \log [\, \log (r_d / r_v) \,] - 0{,}436} \qquad (18)$$

where:

$\boldsymbol{r_d}$ – calculated depression cone radius (Jetel 1982) [m]
$\boldsymbol{r_v}$ – well radius [m]

In case of hydrodynamically perfect well primary conversion difference equals total conversion difference. For the quasi steady–state phase of transient flow under assumption of Jacob logarithmic approximation of Theis well function (Jacob 1946) it is expressed by equation (19) by Jetel (1985):

$$\boldsymbol{d_0 = \log (0{,}183 \cdot \log (2{,}25 \cdot a \cdot t / r_v))} \qquad (19)$$

where:

$\boldsymbol{d_0}$ – primary conversion difference [–]

$\boldsymbol{t}$ – time from the beginning of a pumping test, determining the current size of the calculated depression cone [s]

$\boldsymbol{a}$ – hydraulic diffusivity coefficient (ratio between transmissivity $\boldsymbol{T}$ and water-table storativity $\boldsymbol{S_v}$ or elastic storativity $\boldsymbol{S_p}$; $\boldsymbol{a = T/S}$)

As a preliminary estimate of transmissivity $\boldsymbol{T}$ a value of $\boldsymbol{T_Y}$, expressed from measured value of index $\boldsymbol{Y}$ after equation (3), can be used, and then the first preliminary estimate $\boldsymbol{T_Y}$ = antilog(Y-9). Values of primary conversion difference use to range from -0.3 to 0.3, but values < -0.5 or > 0.5 show "unusual behaviour" of interpreted data, where inspection of input parameters is required (Jetel 1985). In the analysed dataset, average value of primary conversion difference was -0.06, median was 0.11 and standard deviation of $\boldsymbol{d_0}$ values was 0.38. Here, for the 15,886 boreholes, where these values could be calculated, upper and lower 10% percentile was within the interval of <-0.62; 0.27>.

Additional conversion difference

The additional conversion difference is a sum of partial differences, which express effect of all linear as well as nonlinear resistivities to flow in a real well:

$$\boldsymbol{d_d = d_S + d_L + d_C + d_H + d_X} \qquad (20)$$

Additional conversion differences (dimensionless), reflecting the effect of additional linear resistivities, can be separated into skin-effect difference $\boldsymbol{d_S}$ and partial-penetration difference $\boldsymbol{d_L}$.

The skin-effect difference reflects flow resistance originating from well clogging or damage of the natural structure of an aquifer in the near-well zone and resistance caused by narrowing of the active surface of a borehole wall as a result of covering by filter, perforation, etc. Its value is practically not possible to be determined analytically and in calculations it is usually neglected or judged based on analogy (Jetel 1995b).

The partial-penetration difference $\boldsymbol{d_L}$ represents resistance originating as a result of incomplete penetration of aquifer thickness by a well. It is a function of the ratio between theoretical specific capacity of hydrodynamically perfect well $\boldsymbol{q_M}$ and specific capacity of hydrodynamically imperfect well $\boldsymbol{q_L}$:

$$\boldsymbol{d_L = \log q_M / q_L} \qquad (21)$$

More detailed procedures for $\boldsymbol{d_L}$ determination were published by Jetel (1985). In a case when the well partial-penetration adjustment has already been made during the determination of $\boldsymbol{Z_Y}$, the difference does not need to be taken into account, because its influence has been accounted for in the calculation of $\boldsymbol{Z_L}$. The difference cannot be calculated unless the thickness $\boldsymbol{M}$ is known. Such situation can occur mainly in fissured non-stratified aquifers.

The sum of additional differences reflecting nonlinear resistance can be partitioned into turbulence difference $\boldsymbol{d_C}$, expressing the effect of quadratic nonlinear resistance – especially turbulence of flow inside the well – and difference $\boldsymbol{d_X}$, comprising effects of all remaining nonlinear resistance.

The quadratic turbulence difference is significant only when tens or hundreds of litres of water are pumped from a well per second. It rises with pumped quantity, decreases with enlarging the well radius and with increasing transmissivity. Suitable way of its calculation is by means of the equation (Jetel 1985):

$$\boldsymbol{d_C = \log [(\text{antilog}\, d_0 + Q / rT^{0{,}25}) / (\text{antilog}\, d_0)]} \qquad (22)$$

Outseepage interval difference $\boldsymbol{d_H}$ is generally being neglected, because it is disputable by itself. Despite unquestionable existence of an outseepage interval of an unconfined water table, Busch & Luckner (1972) present arguments, which put in doubt its practical reason and its effect on additional drawdown in a well.

Unknown difference $\boldsymbol{d_X}$ is a difference, which together with the skin-effect difference cannot be determined analogically, but together with the skin-effect difference composes residual difference d_Z, essential for the precise determination of the total difference:

$$d_z = d_S + d_X \tag{23}$$

Total conversion difference is at this moment composed of a sum of estimated differences d_0, d_L and d_c and an unknown residual difference.

$$d_z = d - d_0 - d_L - d_c = d_s + d_x \tag{24}$$

The residual difference d_z is usually composed solely by skin-effect difference d_S. During a preliminary estimate it can be neglected, what assumes that:

$$d = d_0 + d_L + d_C \tag{25}$$

In the dataset counting 15,876 interpreted boreholes, average values of partial-penetration difference d_L, quadratic turbulence difference d_C, and outseepage interval difference d_H were 0.37, 0.40 and 0.36, respectively, and their median values were of 0.40, 0.33 and 0.32. Calculation of outseepage interval difference d_H was applied here only in 7,112 cases. Standard deviations values for d_L, d_C, and d_H were 0.30, 0.25 and 0.47; upper and lower 10% percentiles were of <0.12; 0.70>, <0.14; 0.80> and <-0.17; 0.89>.

Based on primary and additional conversion differences, the set of final conversion differences d was prepared: the values there were ranging from -1.78 to 2.70, with median value of 0.18 and average of 0.19. The interval of upper and lower 10% percentiles was <-0.14; 0.49> and the standard deviation of the whole set of all 16,729 final conversion differences d was 0.31.

Using standard specific capacity ^1q and logarithmic conversion difference d, obtained for each well or borehole in equations (1) and (14) for of transmissivity T values or (2) and (15) for hydraulic conductivity K, datasets of these values were developed for 106 outlined aquifer types, where at least 3 pumping tests results on different boreholes were available (Table 3.1). Some authors tried to estimate "regional values" of the logarithmic conversion difference for certain rock types (Olekšák, 2004, Helma, 2007). Other studies correlated values of conversion difference with transmissivity derived by standard interpretation of pumping tests, using equations (12) or (16) – e.g. Jetel (1994) or Helma (2005). In this study, only conversion difference values individually calculated for each borehole were used.

3.4 SPECIFIC-CAPACITY DERIVED VALUES OF HYDRAULIC PARAMETERS FOR INDIVIDUAL ROCK TYPES

A large database of hydrogeological boreholes (wells) containing the date notations for 25,323 wells from all hydrogeological units of the Slovak Republic was developed (Malík et al. 2007). The spatial position of these boreholes is visible in Fig. 3.11. From these, 16,729 pumping tests could be reinterpreted, using the data stored for each borehole. However, the tested wells were unequally distributed in different aquifer types: 9,950 well tests were in Quaternary porous aquifers, and only 6,779 well tests were performed in all other types of pre-Quaternary aquifers. In the process of database development, if possible, each borehole was linked to a certain geological type of pumped aquifer according to screen position (open casing interval), using the Digital Geological Map of Slovakia in the scale of 1:50,000 (Káčer et al., 2005; Map server of the SGIDŠ 2016). It should be also stressed that wells with an ambiguous position of screen were excluded from further processing to obtain a distinct relation of pumped amount to lithological type. In total, 156 general hydrogeological types of aquifers were identified in Quaternary deposits and pre-Quaternary rocks outcropping on the territory of the Slovak Republic, with 31 Quaternary sedimentary types and 125 pre-Quaternary rocks delineated. The list and characteristics of the individual pre-Quaternary aquifer types (Malík et al., 2007), as derived from the Digital Geological Map of Slovakia in a scale of 1:50 000 (Káčer et al. 2005), is in Table 3.1.

If possible, Quaternary deposits were divided into Early Quaternary (Pleistocene) or Late Quaternary (Holocene) groups, but majority of Quaternary deposit types remain undivided (see Table 3.1). Pre-Quaternary aquifer types within Slovakia can be divided into six basic groups according to their stratigraphical age. These are: (a) Neogene sedimentary aquifers; (b) volcanic Neogene aquifers (both lava and volcanoclastic sediments); (c) sedimentary aquifers of Palaeogene age; (d) aquifers in Mesozoic sediments; (e) aquifers in Crystalline and (f) in Palaeozoic rocks. Classification of the individual aquifer types into basic groups is shown in a special column of Table 3.1. The existing aforementioned total of 156 aquifer types (Malík et al. 2007) was derived from the 1,853 individual lithostratigraphical rock types described on the unified legend of the Digital Geological Map of Slovakia (Káčer et al. 2005). The process of unification of lithostratigraphical rock types into aquifer types was based on similarities in lithological content, considering features that were supposed to be the most important for groundwater circulation.

In the interpretation process of linking wells and boreholes with pumping tests to individual aquifer types, however, we were able to find relevant available data from more than 3 objects (wells/boreholes) for only 27 specific types of Quaternary deposits and 79 specific pre-Quaternary aquifer types (Table 3.1). In this way, only data from 16,239 individual pumping tests on boreholes and wells could be exploited, 9,940 well tests for Quaternary aquifers and 6,299 well tests for pre-Quaternary aquifers. The absolute majority (6,895 tests) were interpreted for Quaternary fluvial deposits – sands, sandy gravels and fine to coarse gravels of alluvial plains and low terraces bottom accumulations. Majority of the data for pre-Quaternary aquifer types was obtained from the clay, silt, sand and gravel rock environments and from brackish, lake and fluvial sediments of Neogene age, where 1,364 pumping tests were performed. On the other hand, for 3 Quaternary and 38 pre-Quaternary aquifer types it was not possible to find any relevant hydrogeological borehole or well, while for another one Quaternary and 8 pre-Quaternary aquifer types only less than 3 relevant borehole tests were available. Basic statistical characteristics of the standard specific capacities ^1q (and derived values of the transmissivity ***T*** and hydraulic conductivity coefficients ***K***, calculated for different aquifer types on the Slovak territory are shown in Table 3.1. These were calculated from respective borehole datasets as geometric means ***G(T)*** and ***G(K)***. One should still keep in mind that in the process of rock hydraulic properties assessment the scale effect, i.e., the dependency of hydraulic properties with scale of their measurement (Schulze-Makuch et al. 1999), plays also an important role. From this aspect, pumping tests on boreholes usually represent one of the best sources of information on these parameters. Standard deviation of the transmissivity coefficient logarithm values **σ log T** shown here illustrates the heterogeneity of the spatial distribution of rock hydraulic properties in individual Quaternary and pre-Quaternary aquifer types.

Tab. 3.1 Values of standard specific capacities ^1q [$l \cdot s^{-1} \cdot m^{-1}$] and geometric means ***G(T)*** and ***G(K)*** of derived values of transmissivity ***T*** [$m^2 \cdot s^{-1}$] and hydraulic conductivity ***K*** [$m \cdot s^{-1}$] coefficients, calculated for different aquifer types in Slovakia (Malík et al., 2007).

No.	Description	Origin and classification	Group	n	M(^{1}q)	Md(^{1}q)	G(T)	σ log T	G(K)
1	clayey-loamy-sandy and loamy-stony eluvial deposits of platforms and plains, fossil soils	eluvial and deluvial deposits	Q	11	0.142	0.104	1.46E-04	0.38	2.72E-05
2	undifferentiated deluviums and debris	deluvial deposits	Q	94	0.494	0.444	6.97E-04	0.85	1.55E-04
3	loamy-clayey and sandy loams on slopes	deluvial deposits	Q	31	0.091	0.083	9.71E-05	1.07	2.06E-05
4	mainly loamy-stony (eventually sandy-stony) deluviums and debris	deluvial deposits	Q	123	0.214	0.194	3.21E-04	0.86	5.39E-05
5	periglacial sandy-stony and boulder scree cones (rock collapses and „stone seas“)	deluvial deposits	Q	7	0.273	0.356	4.43E-04	0.50	1.34E-04
6	undifferentiated loamy-stony and boulder landslide deposits	landslide deposits	Q	9	0.502	0.970	3.18E-04	1.15	1.12E-04
7	loess and loess-like loams and runoff loams	eolian – deluvial deposits	Q	3	0.329	0.188	3.34E-04	0.89	8.35E-05
8	mainly fine eolian sands (calcareous or non-calcareous)	eolian and fluvial-eolian deposits	Q	100	0.833	1.000	1.22E-03	0.69	1.16E-04
9	loess and fine sandy loess, calcareous and loess loams in whole	eolian deposits	Q	13	0.110	0.062	1.64E-04	0.89	4.02E-05
10	mostly runoff loams, sandy loams with debris, fine sands and runoff deposits from loess	deluvial-fluvial deposist	Q	18	0.131	0.151	1.56E-04	0.65	4.30E-05
11	loamy to stony-loamy proluvial cones, partly with gravels and sands	deluvial-proluvial deposits	Q	7	0.717	0.603	1.02E-03	0.71	2.46E-04
12	periglacial loams to sandy loams, gravelly-stony loams, boulders and blocks in valleys and slope current deposits	deluvial-solifluction deposits	Q	4	0.014	0.016	1.53E-05	0.20	2.63E-06
13	loamy, sandy to boulder gravels with rock fragments in alluvial cones	proluvial deposits	Q	371	0.798	1.100	1.14E-03	0.78	2.15E-04
14	loams, sandy loams and loamy gravels with rock fragments in floodplain alluvial cones	proluvial deposits	Q	118	0.505	0.547	6.96E-04	0.85	1.81E-04
15	loamy, sandy to boulder gravel s with rock fragments in alluvial cones covered by loess and loess loams	covered deluvial deposits	Q	64	0.479	0.494	6.84E-04	0.75	1.31E-04
16	mostly coarse, boulder to block sandy gravels, sometimes with covered by loess loams	glacifluvial deposits	Q	92	0.699	0.775	9.07E-04	0.86	1.35E-04
17	placer sands and weathered gravels, partly in residues	glacifluvial deposits	Q	4	0.023	0.054	3.63E-05	0.94	6.48E-06
18	sands, sandy gravels and fine to coarse gravels of alluvial plains and low terraces bottom accumulations, covered by flood clayey loams, sandy loams, loamy sands and loamy gravels	covered fluvial deposits	Qh	936	1.257	1.675	1.68E-03	0.77	4.20E-04
19	sands, sandy gravels and fine to coarse gravels of alluvial plains and low terraces bottom accumulations, covered by flood sands and sandy gravels	covered fluvial deposits	Qh	98	1.598	3.239	2.27E-03	0.87	7.45E-04
20	sands, sandy gravels and fine to coarse gravels of alluvial plains and low terraces bottom accumulations	fluvial deposits	Qh	6895	3.005	3.243	4.52E-03	0.76	8.24E-04
21	sands, sandy gravels and fine to coarse gravels of alluvial plains and low terraces bottom accumulations, covered by loess and loess loams	covered fluvial deposits	Qh	147	0.663	0.784	9.10E-04	0.62	2.27E-04
22	sands, sandy gravels and fine to coarse gravels of river terraces, covered by sandy loams and sands	covered fluvial deposits of river terraces	Qp	17	0.285	0.209	3.20E-04	0.75	7.93E-05

No.	Description	Origin and classification	Group	n	M(ᶦq)	Md(ᶦq)	G(T)	σ log T	G(K)
23	sands, sandy gravels and fine to coarse gravels of river terraces (including residual gravels)	fluvial deposits of river terraces	Qp	526	0.734	0.944	9.86E-04	0.76	2.59E-04
24	sands, sandy gravels and fine to coarse gravels of river terraces, covered by loess and loess loams	covered fluvial deposits of river terraces	Qp	227	0.772	1.073	1.08E-03	0.87	2.55E-04
25	peats (peat and bogs), humic peat loams	organic deposits	Q	3	0.340	0.280	4.52E-04	0.19	8.51E-05
26	heaps and dumps	anthropogenic deposits	Q	7	1.620	2.083	2.62E-03	0.35	4.22E-04
27	travertines, tufas, calcareous sinters (freshwater limestones)	chemogenic – organogenic deposits	Q	15	1.712	5.057	2.31E-03	1.36	2.52E-04
28	mostly clays and claystones, variably with limited presence of silts, sands, gravels, diatomites, volcanic tuffs and coal clays with lignite	lake, lacustrine and fluvial Neogene sediments	NG	222	0.204	0.214	4.20E-04	0.68	2.31E-05
29	clays, claystones, silts, sandy clays, sands, tuffites and diatomites with beds and layers of lignite, occasionally also gravels	lake, lacustrine and fluvial Neogene sediments	NG	670	0.178	0.186	3.00E-04	0.80	2.09E-05
30	clays, claystones and siltstones, variably with beds of sandstones, conglomerates, tuffs or limestones	shallow sea sediments and fluvial Neogene sediments	NG	87	0.117	0.135	2.61E-04	0.64	1.15E-05
31	clays, silts, sands and gravels	shallow sea sediments, lake and fluvial Neogene sediments	NG	1364	0.363	0.372	5.99E-04	0.79	4.29E-05
32	clays, silts, sands, gravels, conglomerates and limestones	shallow sea sediments and fluvial Neogene sediments	NG	63	0.138	0.151	1.65E-04	1.01	1.09E-05
33	mostly clays, claystones and sands	shallow sea sediments and lake Neogene sediments	NG	227	0.135	0.162	2.13E-04	0.81	1.25E-05
34	mostly silts and sands	shallow sea Neogene sediments	NG	16	0.646	0.447	9.39E-04	0.38	4.88E-05
35	mostly sands and gravels or conglomerates	shallow sea and fluvial Neogene sediments	NG	167	0.331	0.372	6.75E-04	0.81	3.16E-05
36	claystones and sandstones with evaporites	shallow sea Neogene sediments	NG	41	0.087	0.191	9.99E-05	1.13	7.58E-06
37	claystones, siltstones and sandstones with beds of conglomerates and tuffs	shallow sea Neogene sediments	NG	32	0.123	0.148	1.88E-04	0.89	8.78E-06
38	mostly siltstones and sandstones, variably with beds of claystones and tuffs	shallow sea Neogene sediments	NG	70	0.105	0.117	3.12E-04	0.58	1.20E-05
39	mostly sandstones and conglomerates, to a lesser extent tuffs, tuffites, limestones	shallow sea Neogene sediments	NG	9	0.891	0.661	2.37E-03	1.04	1.42E-04
40	conglomerates and breccias, occasionally limestones, claystones, sandstones	shallow sea Neogene sediments	NG	54	0.427	0.468	8.15E-04	1.01	4.09E-05
41	limestones, variably with beds of claystones, sandstones or conglomerates	shallow sea Neogene sediments	NG	27	0.240	0.427	3.18E-04	0.79	3.20E-05
42	pyroclastic breccias, agglomerates and tuffs of basalts and basaltic andesites (including pyroclastic flow sediments)	volcanic Neogene rocks: basalts and basaltic andesites	VN	8	1.259	1.585	1.97E-03	0.44	2.91E-05
43	plutons and intrusions of granodiorite, diorite and dioritic porphyries	subvolcanic intrusions	VN	3	0.036	0.019	4.91E-05	0.56	9.43E-07
44	laccoliths, sills, dikes and volcanic necks of andesite porphyries and andesites, including beds of intrusive and tuffaceous breccias	intravolcanic intrusions	VN	6	0.087	0.039	1.76E-04	1.24	2.41E-06
45	complexes of propylitised andesites and andesitic porphyries	metamorphic intravolcanic intrusions and volcanites	VN	3	0.282	0.209	1.16E-03	0.86	3.54E-05
46	protrusions, extrusive domes and short lava flows (dome flows) of andesites and their extrusive breccias	volcanic Neogene rocks: andesites	VN	58	0.102	0.089	1.36E-04	0.85	3.25E-06
47	lava flows of andesites and their mostly block lava breccias	volcanic Neogene rocks: andesites	VN	85	0.166	0.178	2.86E-04	0.86	5.79E-06
48	pyroclastic breccias, agglomerates and tuffs of andesites (including redeposited pyroclastics)	volcanic Neogene rocks: andesites	VN	57	0.174	0.174	3.32E-04	0.88	4.92E-06
49	tuffs of andesites (including ignimbrites and redeposited tuffs with admixture of epiclastics)	volcanic Neogene rocks: andesites	VN	32	0.089	0.095	1.37E-04	0.78	6.05E-06
50	hyaloclastic breccias and epiclastic volcanic breccias and conglomerates of andesites with rare beds of sandstones	volcanic Neogene rocks: andesites	VN	206	0.229	0.170	3.99E-04	0.85	1.11E-05
51	epiclastic volcanic and tuffaceous sandstones of andesites, variably with admixture of small-grained breccias, conglomerates and redeposited tuffs	volcanic Neogene rocks: sediments of andesites	VN	203	0.331	0.339	6.30E-04	0.64	2.76E-05

No.	Description	Origin and classification	Group	n	M(¹q)	Md(¹q)	G(T)	σ log T	G(K)
52	epiclastic volcanic and tuffaceous sandstones and siltstones of andesites	volcanic Neogene rocks: sediments of andesites	VN	34	0.178	0.145	3.52E-04	0.83	2.28E-05
53	tuffaceous siltstones and claystones of andesites	volcanic Neogene rocks: sediments of andesites	VN	21	0.575	0.912	1.00E-03	0.97	4.45E-05
54	intrusions, laccoliths, sills and dikes of dacitic to rhyolitic porphyries and dacites to rhyolites, occasionally intrusive breccias	volcanic Neogene rocks: dacite to rhyolite intravolcanic intrusions	VN	5	0.046	0.039	8.11E-05	0.26	2.39E-06
55	tuffs of dacites to rhyolites (including ignimbrites and redeposited tuffs with admixture of epiclastics)	volcanic Neogene rocks: dacites to rhyolites	VN	15	0.138	0.123	1.81E-04	1.01	1.11E-05
56	hyaloclastic breccias and epiclastic volcanic breccias and conglomerates of dacites to rhyolites, variably with beds of sandstones and redeposited tuffs	volcanic Neogene rocks: dacites to rhyolites	VN	3	0.023	0.043	3.27E-05	0.63	1.93E-06
57	epiclastic volcanic sandstones and redeposited tuffs of dacites to rhyolites, variably with admixture of small-grained epiclastics	volcanic Neogene rocks: dacite to rhyolite volcanites/sediments	VN	4	0.105	0.107	3.00E-04	0.53	9.93E-06
58	calcareous siltstones and claystones, occasionally with coal intercalations	shallow sea sediments of the Buda Palaeogene	PG	116	0.054	0.068	1.15E-04	0.92	4.66E-06
59	sands, marly and calcareous sands, decomposed sandstones and siltstones	shallow sea sediments of the Buda Palaeogene	PG	16	0.126	0.141	3.44E-04	0.56	1.29E-05
60	gravels, decomposed conglomerates	shallow sea sediments of the Buda Palaeogene	PG	3	0.151	0.120	1.40E-04	0.25	1.34E-05
61	claystones, calcareous claystones and marls and layers with overwhelming claystones/marlstones over sandstones, including menilite layers	marine sediments of Inner Carpathian Palaeogene	PG	127	0.107	0.117	1.73E-04	0.81	1.39E-05
62	claystone flysch – flysch with prevailing claystones or marlstones	flysch sediments of Inner Carpathian Palaeogene and Late Cretaceous	PG	7	0.010	0.012	9.60E-06	0.57	4.70E-07
63	normal flysch – claystones/marls, siltstones and sandstones	flysch sediments of Inner Carpathian Palaeogene and Late Cretaceous	PG	220	0.102	0.102	1.49E-04	0.77	1.11E-05
64	sandstone flysch – flysch with prevailing sandstones	flysch sediments of Inner Carpathian Palaeogene and Late Cretaceous	PG	13	0.120	0.100	1.21E-04	0.65	5.51E-06
65	conglomerate flysch – flysch with prevailing conglomerates	flysch sediments of Inner Carpathian Palaeogene and Late Cretaceous	PG	4	0.158	0.178	3.94E-04	0.62	2.06E-05
66	sandstones with thin intercalations of claystones	flysch sediments of Inner Carpathian Palaeogene and Late Cretaceous	PG	120	0.123	0.145	2.02E-04	0.74	7.92E-06
67	multicomponent conglomerates and breccias, variably with beds of sandstones	sea sediments and subaqueous slides of Inner Carpathian Palaeogene	PG	17	0.068	0.078	7.70E-05	0.80	3.68E-06
68	calcareous breccias and conglomerates, sandy limestones, and limestones, variably with beds of sandstones, occasionally also marlstones	sea sediments of Inner Carpathian Palaeogene and Late Cretaceous	PG	60	0.251	0.209	3.58E-04	0.99	1.58E-05
69	claystones, calcareous claystones and marls and layers with dominantly prevailing claystones/marlstones over sandstones, including menilite layers	sediments of Flysch Belt and Klippen Belt	PG	39	0.040	0.027	4.31E-05	0.99	4.57E-06
70	claystone flysch – flysch with prevailing claystones, siltstones or marlstones	sediments of Flysch Belt and Klippen Belt	PG	86	0.074	0.069	1.01E-04	1.05	6.39E-06
71	normal flysch – claystones/marls, siltstones and sandstones (or feldspar sandstones)	sediments of Flysch Belt and Klippen Belt	PG	65	0.049	0.050	6.03E-05	0.74	6.05E-06
72	carbonate flysch – calcareous sandstones and marls	sediments of Flysch Belt and Klippen Belt	PG	52	0.040	0.029	4.20E-05	0.86	3.12E-06
73	sandstone flysch – flysch with prevailing sandstones (or feldspar sandstones)	sediments of Flysch Belt and Klippen Belt	PG	296	0.178	0.204	2.22E-04	0.83	1.45E-05
74	conglomerate flysch – flysch with prevailing conglomerates	sediments of Flysch Belt and Klippen Belt	PG	3	0.085	0.098	3.65E-04	0.31	3.02E-06
75	sandstones (feldspar sandstones), variably with thin intercalations of claystones	sediments of Flysch Belt and Klippen Belt	PG	4	0.025	0.023	2.14E-05	0.50	2.40E-06
76	limestones, sandy limestones, marly limestones, quartzitic limestones, occasionally dolomites or silicites/radiolarites	sediments of Flysch Belt and Klippen Belt	PG	13	0.093	0.089	1.16E-04	0.72	9.74E-06
77	claystones, shales, marls	Jurassic and Cretaceous sediments of Inner West Carpathians	MZ	3	0.117	0.060	1.40E-04	0.78	3.94E-06

No.	Description	Origin and classification	Group	n	M(¹q)	Md(¹q)	G(T)	σ log T	G(K)
78	claystones/shales and sandstones (also flysch), variably also beds of sandy limestones, conglomerates, silicites	Jurassic and Cretaceous sediments of Inner West Carpathians	MZ	21	0.063	0.051	9.44E-05	0.61	4.25E-06
79	conglomerates, sandstones and shales/marls, occasionally also limestones	Jurassic and Cretaceous sediments of Inner West Carpathians	MZ	12	0.095	0.148	1.36E-04	0.90	3.79E-06
80	shales/marls and limestones, silicitic limestones, nodular limestones, quartzitic/ radiolaritic limestones	Jurassic and Cretaceous sediments of Inner West Carpathians	MZ	16	0.437	0.631	6.88E-04	1.36	2.85E-05
81	limestones, marly limestones and/ or quartzitic/silicitic limestones with intercalations of silicites and/or shales/ marlstones	Jurassic and Cretaceous sediments of Inner West Carpathians	MZ	55	0.245	0.417	3.56E-04	1.06	8.49E-06
82	limestones, marly limestones, crinoid limestones, nodular limestones, quartzitic/ silicitic limestones, eventually sandy limestones, calcareous sandstones/ conglomerates	Jurassic and Cretaceous sediments of Inner West Carpathians	MZ	30	0.309	0.490	5.24E-04	1.32	1.29E-05
83	Cellular dolomites, dolomitic breccias, rauhwackes	tectonically reduced carbonate rocks	MZ	6	0.309	0.372	5.53E-04	0.51	4.05E-06
84	metamorphic limestones, carbonates	metamorphic sediments of Triassic	MZ	5	0.603	0.331	9.32E-04	0.66	8.47E-06
85	limestones, quartzitic limestones, nodular limestones, limestones with cherts	sediments of Middle and Late Triassic	MZ	34	1.622	3.236	3.52E-03	0.81	1.91E-04
86	sandstones, shales, variably beds or intercalations of limestones, dolomites, evaporites, metatuffs, silicites	sediments of Middle and Late Triassic	MZ	20	0.234	0.182	3.41E-04	0.93	1.34E-05
87	limestones	sediments of Middle and Late Triassic	MZ	238	0.339	0.407	6.19E-04	1.06	1.06E-05
88	limestones and dolomitic limestones, dolomites	sediments of Middle and Late Triassic	MZ	3	24.547	40.738	4.64E-02	0.47	6.00E-04
89	dolomites	sediments of Middle and Late Triassic	MZ	438	0.575	0.589	1.04E-03	0.86	2.37E-05
90	dolomites with intercalations of shales	sediments of Middle and Late Triassic	MZ	23	0.724	0.676	1.43E-03	0.71	2.57E-05
91	sandstones, variegated shales, marly shales, marls, marly limestones, limestones	Early Triassic sediments	MZ	39	0.071	0.065	1.06E-04	0.79	3.50E-06
92	shales, sandy shales with intercalations of sandstones	Early Triassic sediments	MZ	19	0.191	0.151	2.83E-04	0.82	1.12E-05
93	quartzites, quartzitic sandstones, sandstones	Early Triassic sediments	MZ	36	0.120	0.126	1.76E-04	0.86	7.29E-06
94	unsorted shales/phyllites, sandstones, feldspar sandstones, conglomerates, sporadically also intercalations of volcanic rocks	Late Palaeozoic sediments	PZ	20	0.030	0.032	2.92E-05	0.59	1.80E-06
95	shales/phyllites, sandy shales, variably with sporadic intercalations of sandstones, conglomerates, dolomites or volcanic rocks	Late Palaeozoic sediments	PZ	6	0.076	0.019	7.54E-05	1.29	1.68E-06
96	sandstones, feldspar sandstones, sandy shales, shales/phyllites, occasionally intercalations of dolomites, conglomerates, and phosphatic sediments	Late Palaeozoic sediments	PZ	14	0.045	0.074	6.77E-05	0.77	3.01E-06
97	sandstones, feldspar sandstones, variably with intercalations of shales/phyllites, conglomerates, volcanic rocks	Late Palaeozoic sediments	PZ	7	0.129	0.145	1.78E-04	0.86	4.91E-06
98	metamorphic dolomites, magnesites, siderites	metamorphic sediments of Late Palaeozoic	PZ	4	2.089	2.089	6.20E-03	0.70	4.90E-05
99	acidic volcanite rocks of Late Palaeozoic	volcanites of Late Palaeozoic	PZ	5	0.120	0.229	1.40E-04	1.21	8.59E-06
100	basic volcanite rocks of Late Palaeozoic	volcanites of Late Palaeozoic	PZ	3	0.039	0.027	1.64E-04	0.46	3.86E-06
101	amphibolites, amphibolite gneisses, gabbrodiorites, metabasalts and basic metavolcanites	Early Palaeozoic metamorphic volcanites	PZ	5	0.007	0.016	3.59E-06	0.72	3.04E-07
102	metarhyolites, acidic metavolcanites	Early Palaeozoic metamorphic volcanites	PZ	8	0.062	0.050	1.04E-04	0.83	3.51E-06
103	phyllites, variably with beds and intercalations of metamorphic sandstones and feldspar sandstones, occasionally also metacarbonates and metavolcanites	Early Palaeozoic metamorphic sediments	PZ	52	0.026	0.023	4.26E-05	0.84	2.35E-06
104	acidic and intermediary igneous rocks (granitoids) – granites, granodiorites, tonalites, pegmatites and aplites	Crystalline magmatic rocks	CR	95	0.043	0.038	6.39E-05	0.74	2.07E-06

No.	Description	Origin and classification	Group	n	M(¹q)	Md(¹q)	G(T)	σ log T	G(K)
105	metamorphic rocks of medium to higher degree – mostly slates, slate gneisses, paragneisses, metaquartzites	Crystalline metamorphic rocks	CR	18	0.028	0.027	3.45E-05	0.75	1.42E-06
106	high degree metamorphic rocks – orthogneisses, migmatitic gneisses, migmatites	Crystalline metamorphic rocks	CR	11	0.017	0.014	1.07E-05	0.95	4.65E-07

Explanation of abbreviations: ***n*** *– number of interpreted hydraulic tests on hydrogeological boreholes and wells;* ***M(¹q)*** *– arithmetic mean of the standard specific capacity* ***¹q****;* ***Md(¹q)*** *– median value of the standard specific capacity* ***¹q****;* ***G(T)*** *– geometrical mean of the transmissivity coefficient* ***T****;* **σ log T***– standard deviation of the transmissivity coefficient logarithm values;* ***G(K)*** *– geometrical mean of the hydraulic conductivity coefficient* ***T****;* ***Q*** *– group of undistinguished Quaternary deposits;* ***Qh*** *– group of Late Quaternary (Holocene) deposits;* ***Qp*** *– group of Early Quaternary (Pleistocene) deposits;* ***NG*** *– group of Neogene sediments;* ***VN*** *– group of Neogene volcanic rocks;* ***PG*** *– group of Palaeogene sediments;* ***MZ*** *– group of Mesozoic sediments;* ***PZ*** *– group of Palaeozoic sediments;* ***CR*** *– group of Crystalline rocks.*

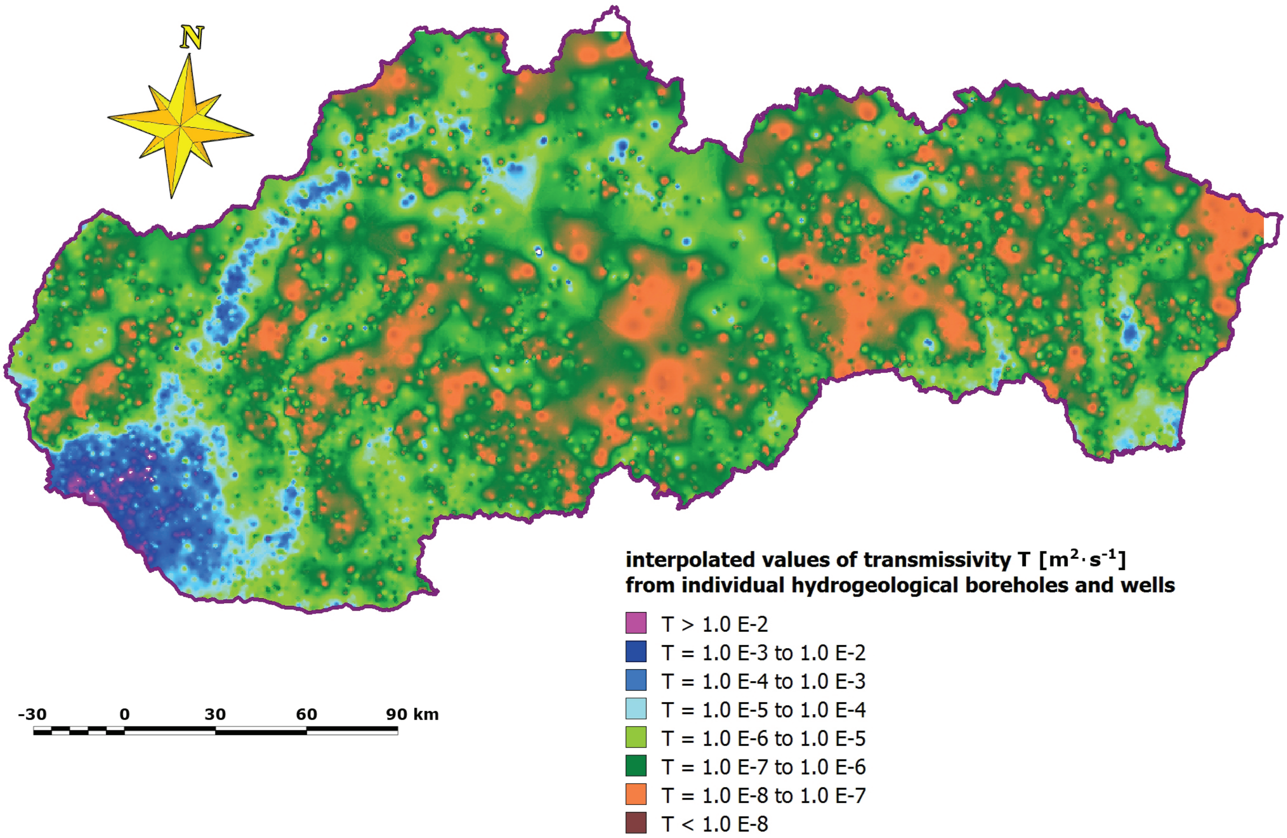


Fig. 3.19 Interpolated values of transmissivity coefficient ***T*** *set by interpretation of specific capacity from pumping tests on 16,729 individual wells and hydrogeological boreholes in Slovakia.*

Based on the results of individual pumping tests on hydrogeological boreholes and wells, interpolated maps of transmissivity ***T*** and hydraulic conductivity coefficients ***K*** could be constructed, using inverse distance weighting (IDW) method of values' logarithms (***log T*** and ***log K***) interpolation (Figs. 3.19 and 3.20).

Interpolation of hydraulic parameters, as shown on Figs. 3.19 and 3.20 however, ignores geological settings and areal distribution of individual rock or aquifer types. Therefore, mean values of transmissivity ***T*** and hydraulic conductivity ***K*** attributed to aforementioned 31 Quaternary sedimentary types of aquifers and 125 pre-Quaternary aquifers delineated on the territory of the Slovak Republic can be constructed as seen on Figs. 3.21 and 3.22. It should be noted, that for those aquifer types (1 Quaternary and 8 pre-Quaternary) where relevant available borehole data were available from less than 3 objects (wells/boreholes), values of these hydraulic parameters were derived from these, and in the cases without presence of any tested hydrogeological object (3 Quaternary and 38 pre-Quaternary), a rough estimate of transmissivity and hydraulic conductivity mean values was applied.

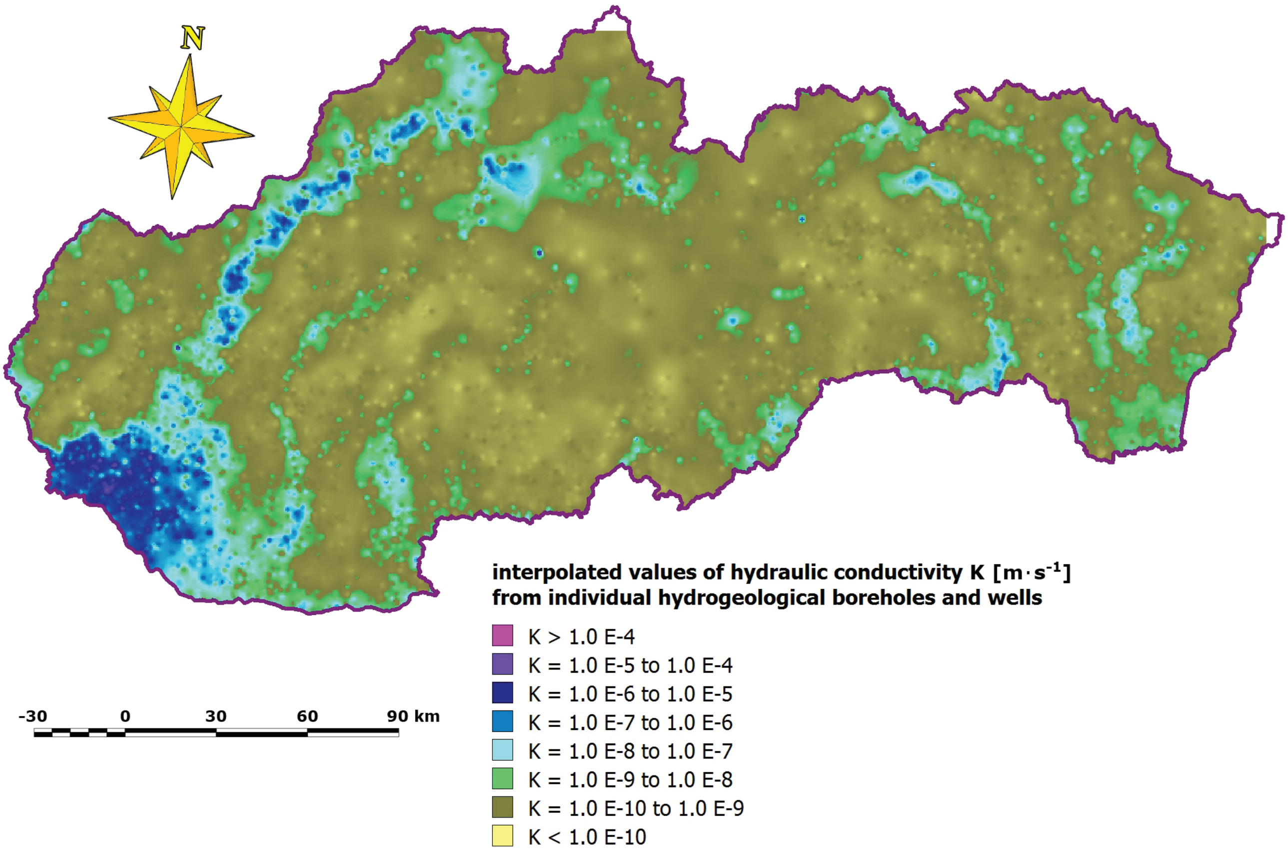


*Fig. 3.20 Interpolated values of hydraulic conductivity **K** set by interpretation of specific capacity from pumping tests on 16,729 individual wells and hydrogeological boreholes in Slovakia.*

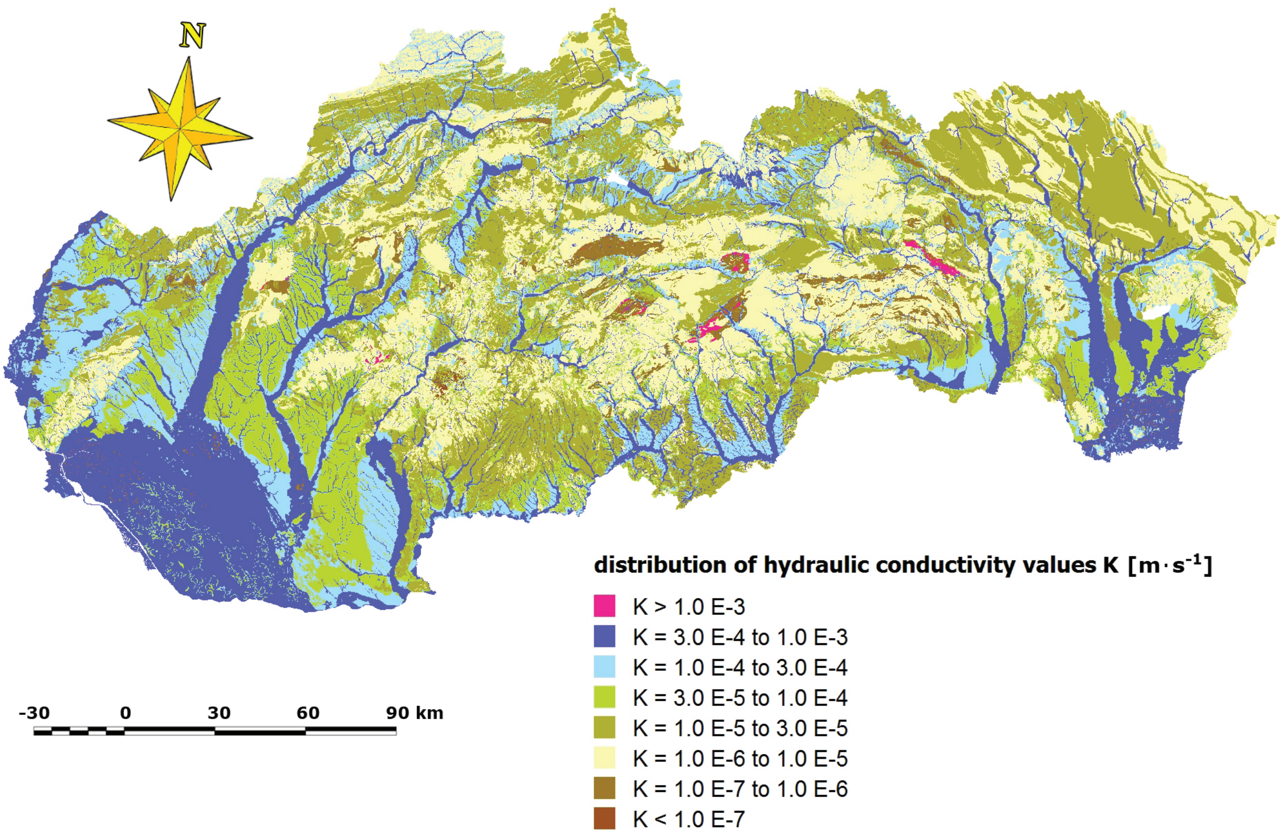


Fig. 3.21 Mean values of transmissivity set for 156 different aquifer types (31 Quaternary and 125 pre-Quaternary) delineated on the Slovak territory.

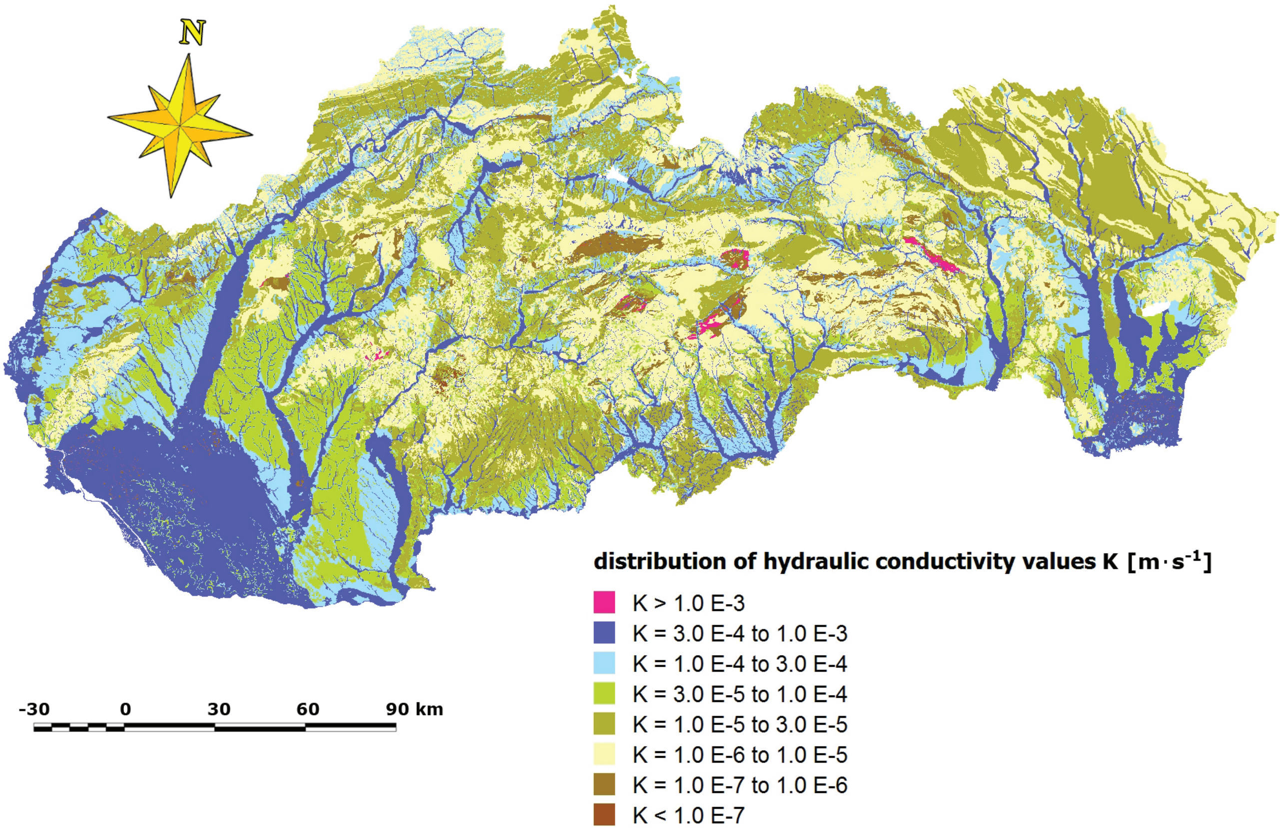


Fig. 3.22 Mean values of hydraulic conductivity set for 156 different aquifer types (31 Quaternary and 125 pre-Quaternary) delineated on the Slovak territory.

Conductive hydraulic parameters' values (both transmissivity and hydraulic conductivity, derived by classical pumping tests interpretation from drawdown in observation piezometers, or derived only from specific capacity as described above) show a log-normal statistical distribution and high heterogeneity. The statistical evaluation of these hydraulic parameters therefore should be based on comparison of geometric mean values ***G(T)*** as shown in Table 3.1. Here, comparison of median ***Md(^{1}q)*** and arithmetical average ***M(^{1}q)*** values of specific capacity ***^{1}q*** can indicate the type of statistical distribution of the data. Values of standard deviation of the transmissivity coefficient logarithm values ***σ log T***, also shown in Table 3.1 mark the areal inhomogeneity of aquifer permeability. Comparing the transmissivity values of Quaternary and pre-Quaternary aquifer types, the median value of 27 Quaternary aquifers ***T*** is $6.96 \cdot 10^{-4}$ $m^2 \cdot s^{-1}$ vs. $1.88 \cdot 10^{-4}$ $m^2 \cdot s^{-1}$ of 79 pre-Quaternary aquifer types. The difference is less than half of one order magnitude, but still underlines more permeable hydraulic behaviour of Quaternary deposits as a whole.

Analysing Quaternary deposits' transmissivity in more detail, the highest ***G(T)*** value is found in fluvial deposits of alluvial plains and low terraces bottom accumulations – sands, sandy gravels and fine to coarse gravels – No. 20 in Table 3.1 – where data from already 6,895 boreholes give the mean ***T*** value of $4.52 \cdot 10^{-3}$ $m^2 \cdot s^{-1}$. Such data should be possibly found elsewhere and mark the importance of river flood plains from the water management point of view. Anthropogenic deposits such as heaps and dumps, but also chemogenic and organogenic deposits – travertines, tufas, calcareous sinters (freshwater limestones; Nos. 26 and 27) also show high mean transmissivity values ($2.62 \cdot 10^{-3}$ and $2.31 \cdot 10^{-3}$ $m^2 \cdot s^{-1}$) but only limited number of boreholes with pumping tests is linked to these (7 resp. 15). From the relevant groups (≥ 30 pumping test performed), covered fluvial deposits such as sands, sandy gravels and fine to coarse gravels of alluvial plains and low terraces bottom accumulations, covered by flood sands and sandy gravels (98 boreholes; $2.27 \cdot 10^{-3}$ $m^2 \cdot s^{-1}$; No. 19) or the same fluvial deposits covered by flood clayey loams, sandy loams, loamy sands and loamy gravels (936 boreholes; $1.68 \cdot 10^{-3}$ $m^2 \cdot s^{-1}$; No. 18) take the next most permeable position. From the bottom position of mean transmissivity value in Quaternary aquifers, periglacial loams to sandy loams, gravelly-stony loams, boulders and blocks in valleys and slope current deposits (deluvial and solifluction deposits; No. 12) can be considered as the least permeable ($1.53 \cdot 10^{-5}$ $m^2 \cdot s^{-1}$), but this value is based only on the results of 4 pumping tests. Similar (both in small permeability and number of 4 tested boreholes) are glacifluvial deposits of placer sands and weathered gravels (No. 17) where ***G(T)*** of $3.63 \cdot 10^{-5}$ $m^2 \cdot s^{-1}$ was found. Only the third least permeable Quaternary deposit type from the bottom – loamy-clayey and sandy loams as deluvial deposits on slopes has higher number (31) of relevant pumping tests, showing the mean transmissivity of $9.71 \cdot 10^{-5}$ $m^2 \cdot s^{-1}$ (No. 3 in Table 3.1).

From the relevant aquifer type groups of pre-Quaternary rocks (≥ 30 pumping test performed), limestones, quartzitic limestones, nodular limestones, limestones with cherts (Middle and Late Triassic; No. 85 in Table 3.1) showed the highest mean values (***M(¹q)*** and ***Md(¹q)*** of specific capacity ***¹q*** as well as of transmissivity ***T*** (3.236 $l \cdot s^{-1} \cdot m^{-1}$; $3.52 \cdot 10^{-3}$ $m^2 \cdot s^{-1}$ from 34 evaluated pumping tests). Dolomites of the Middle and Late Triassic (No. 89) were in the second place (0.589 $l \cdot s^{-1} \cdot m^{-1}$; $1.04 \cdot 10^{-3}$ $m^2 \cdot s^{-1}$; 438 pumping tests), followed by (No. 40) shallow sea sediments of Neogene age such as conglomerates and breccias, occasionally limestones, claystones, sandstones (0.468 $l \cdot s^{-1} \cdot m^{-1}$; $8.15 \cdot 10^{-4}$ $m^2 \cdot s^{-1}$; 54 pumping tests). On the opposite side of permeability scale, calcareous sandstones and marls as carbonate flysch sediments of West Carpathian Flysch Belt and Klippen Belt (No. 72 in Table 3.1; 0.029 $l \cdot s^{-1} \cdot m^{-1}$; $4.20 \cdot 10^{-5}$ $m^2 \cdot s^{-1}$; 52 pumping tests) and phyllites, variably with beds and intercalations of metamorphic sandstones and feldspar sandstones, occasionally also metacarbonates and metavolcanites (No. 103), metamorphic sediments of Early Palaeozoic (0.023 $l \cdot s^{-1} \cdot m^{-1}$; $4.26 \cdot 10^{-5}$ $m^2 \cdot s^{-1}$; 52 pumping tests) stand for the lowermost ***G(T)*** values sufficiently documented by more than 30 borehole tests. Early Palaeozoic metamorphic volcanites – amphibolites, amphibolite gneisses, gabbrodiorites, metabasalts and basic metavolcanites (No. 101) can be considered as even showing lesser transmissivity ($3.59 \cdot 10^{-6}$ $m^2 \cdot s^{-1}$), but this value is resulting only from 5 borehole pumping tests.

Comparing regional hydraulic conductivity values derived from single borehole pumping tests specific capacity data as geometric means ***G(K)*** for individual Quaternary and pre-Quaternary aquifer types, we can find more contrasting values than in the case of transmissivities. The difference between Quaternary and pre-Quaternary group median is one and a half order of magnitude ($1.34 \cdot 10^{-4}$ $m \cdot s^{-1}$ vs. $8.59 \cdot 10^{-6}$ $m \cdot s^{-1}$) what means that ***K*** in Quaternary aquifers are in general 15.4 times higher than in the pre-Quaternary ones. This is also caused by the fact that the median value of aquifer thickness in Quaternary was only 4.5 meters (average of 5.0 m), while in pre-Quaternary aquifer types it reached 22.8 m (and average of 32.0 m).

The highest regional hydraulic conductivity values ***G(K)*** in the whole dataset (both Quaternary and pre-Quaternary) can be attributed to the same deposits for which also the highest transmissivity was found: No. 20 in Table 3.1, the fluvial deposits of alluvial plains and low terraces bottom accumulations – sands, sandy gravels and fine to coarse gravels – with the mean ***K*** value of $8.24 \cdot 10^{-4}$ $m \cdot s^{-1}$ (6,895 borehole tests). The next member of this order are (No. 19) sands, sandy gravels and fine to coarse gravels of alluvial plains and low terraces bottom accumulations, covered by flood sands and sandy gravels ($7.45 \cdot 10^{-4}$ $m^2 \cdot s^{-1}$; 98 borehole tests). Mean hydraulic conductivity of heaps and dumps (anthropogenic deposits with ***K*** of $4.22 \cdot 10^{-4}$ $m \cdot s^{-1}$) could take the third place in this "virtual hydraulic conductivity competition", but with only 7 tested boreholes this value can be considered to be less decisive. From the relevant groups (≥ 30 pumping test performed) sands, sandy gravels and fine to coarse gravels of alluvial plains and low terraces bottom accumulations, covered by flood clayey loams, sandy loams, loamy sands and loamy gravels (No. 18) can take the next place (936 boreholes; $4.20 \cdot 10^{-4}$ $m \cdot s^{-1}$). Quaternary deposits with relatively low hydraulic conductivity can be found in the aquifer types (No. 12) of periglacial loams to sandy loams, gravelly-stony loams, boulders and blocks in valleys and slope current deposits (deluvial and solifluction deposits; $2.63 \cdot 10^{-6}$ $m \cdot s^{-1}$) and (No. 17) glacifluvial deposits of placer sands and weathered gravels ($6.48 \cdot 10^{-6}$ $m \cdot s^{-1}$). However, in both cases, only 4 representative borehole tests were performed. More relevant results (31 tests) were attributed to loamy-clayey and sandy loams as deluvial deposits on slopes (No. 3 in Table 3.1), where the mean hydraulic conductivity value of $2.06 \cdot 10^{-5}$ $m \cdot s^{-1}$ makes these deposits to be the third less permeable Quaternary aquifer type.

In terms of hydraulic conductivity, from the pre-Quaternary rocks where ≥ 30 pumping test can be attributed to individual aquifer type, the highest value of $1.91 \cdot 10^{-4}$ $m \cdot s^{-1}$ is again (as in the transmissivity chart) assigned to No. 85 (in Table 3.1): limestones, quartzitic limestones, nodular limestones, limestones with cherts of Middle and Late Triassic, where 34 aquifer tests could be evaluated. These are followed by (No. 40) shallow sea sediments of Neogene age – conglomerates and breccias, occasionally limestones, claystones, sandstones ($4.09 \cdot 10^{-5}$ $m \cdot s^{-1}$; 54 pumping tests) and on the third place, surprisingly by shallow sea sediments, lake and fluvial sediments of Neogene age represented by clays, silts, sands and gravels where from 1,364 pumping tests, mean ***K*** value of $4.29 \cdot 10^{-5}$ $m \cdot s^{-1}$ was calculated. As opposite rock environment form the hydraulic conductivity point of view (if only ≥ 30 borehole tests are considered) can be considered crystalline magmatic rocks – acidic and intermediary igneous rocks (granitoids) – granites, granodiorites, tonalites, pegmatites and aplites. Here, reinterpretation of 95 single borehole pumping tests lead to estimation of mean hydraulic conductivity value of $2.07 \cdot 10^{-6}$ $m \cdot s^{-1}$ (No. 104 in Table 3.1). Very similar ***G(K)*** value of $2.35 \cdot 10^{-6}$ $m \cdot s^{-1}$ was found in the case of phyllites, variably with beds and intercalations of metamorphic sandstones and feldspar sandstones, occasionally also metacarbonates and metavolcanites (No. 103, 52 pumping tests). Calcareous sandstones and marls as carbonate flysch sediments of West Carpathian Flysch Belt and Klippen Belt (No. 72 with 52 reinterpreted pumping tests) with the mean ***K*** value of $3.12 \cdot 10^{-6}$ $m \cdot s^{-1}$ can be considered as the next pre-Quaternary rock type with arguably the third lowest hydraulic conductivity.

It should be stressed out that hydraulic parameters – both transmissivity and hydraulic conductivity – are irregularly distributed also in individual delineated aquifer types. Values of ***σ log T*** standard deviation, the parameter that shows the areal inhomogeneity of aquifer permeability, are within the range of 0.19 – 1.36, with the mean of 0.78 and median of 0.80. This means that hydraulic parameters can be standardly found in the range of one or even two orders of magnitude within one aquifer type and more detailed investigations should be performed on each site to find their local representative values.

3.5 CONCLUSIVE REMARKS

Using the data from the database of hydrogeological boreholes and wells on the territory of the Slovak Republic, maintained by SGIDŠ, 16,729 pumping tests were reinterpreted for rock hydraulic properties assessment – hydraulic conductivity ***K*** and transmissivity ***T***. Methodology of the reinterpretation process is based mostly on works of Jetel (1985, 1995a) and is described in detail in previous chapters. Each borehole (if possible from the available information on screen position / open casing interval) was also linked to the relevant type of pumped aquifer. Ignoring borehole tests on objects with ambiguous screen position, 9,940 well tests could be used for better characterisation of Quaternary aquifers and 6,299 well tests for pre-Quaternary aquifers. From 156 delineated aquifer types (Malík et al. 2007), with 31 Quaternary deposit types and 125 pre-Quaternary rock types identified on the Slovak territory, relevant available data from more than 3 objects (wells/boreholes) were found for only for 27 specific aquifer types in Quaternary deposits and 79 pre-Quaternary aquifer types. Still, the information obtained by this analysis (see Table 3.1) can serve as a good base for further aquifer characterisation and understanding of natural areal distribution of hydraulic properties of rock environment.

Completing the interpretation process and attribution of hydraulic conductivity ***K*** and transmissivity ***T*** values from individual boreholes and wells to delineated aquifer types, these were categorised according to classification principles of Jetel (1982) for hydraulic conductivity (Table 3.2) and Krásný (1986, 1993) for transmissivity (Table 3.3).

Tab. 3.2 Results of borehole tests reinterpretation for hydraulic conductivity values on individual hydrogeological boreholes and wells, as well as their geometric means attributed to individual aquifer types, categorised according to Jetel (1982).

Category No.	Range of hydraulic conductivity values [$m \cdot s^{-1}$]	Category description	Number of boreholes in the category	Abundance of boreholes in the category	Number of aquifer types in the category	Abundance of aquifer types in the category
I.	> 1·E-2	very highly permeable	409	2%	0	0%
II.	1·E-3 to 1·E-2	highly permeable	4,007	24%	0	0%
III.	1·E-4 to 1·E-3	enough permeable	5,630	34%	20	19%
IV.	1·E-5 to 1·E-4	moderately permeable	3,704	22%	41	39%
V.	1·E-6 to 1·E-5	rather poorly permeable	2,015	12%	41	39%
VI.	1·E-7 to 1·E-6	poorly permeable	714	4%	4	4%
VII.	1·E-8 to 1·E-7	extremely poorly permeable	191	1%	0	0%
VIII.	< 1·E-8	slightly permeable	59	0%	0	0%
TOTAL:			16,729	100%	106	100%

Tab. 3.3 Results of borehole tests reinterpretation for transmissivity values on individual hydrogeological boreholes and wells, as well as their geometric means attributed to individual aquifer types, categorised according to Krásný (1986, 1993).

Class of transmissivity magnitude	Range of transmissivity values [$m^2 \cdot s^{-1}$]	Designation of transmissivity magnitude	Number of boreholes in the category	Abundance of boreholes in the category	Number of aquifer types in the category	Abundance of aquifer types in the category
I.	> 1·E-2	very high	3,166	19%	1	1%
II.	1·E-3 to 1·E-2	high	6,417	38%	17	16%
III.	1·E-4 to 1·E-3	intermediate	4,518	27%	66	62%
IV.	1·E-5 to 1·E-4	low	2,021	12%	20	19%
V.	1·E-6 to 1·E-5	very low	493	3%	2	2%
VI.	1·E-7 to 1·E-6	imperceptible	95	1%	0	0%
VII.	1·E-8 to 1·E-7	significantly slight	16	0%	0	0%
VIII.	< 1·E-8	very slight	3	0%	0	0%
TOTAL:			16,729	100%	106	100%

Looking at hydraulic conductivity classification of individual borehole tests results (Table 3.2), we can conclude that individual borehole tests could be classified into all eight categories, but absolute majority of these is classified within four categories (II. to V.), where 93% of individual boreholes tests belong. If these data are attributed to aquifer types, again only four categories are covered by the data (III. to VI.), but 96% of 106 classified aquifer types belong only to three categories (III. to V.). This can be partly explained by the fact that negative reports from hydrogeological boreholes ("zero" or very low yield) are less frequently sent to archives, but still the data concentration into four orders of magnitude (individual borehole tests) or even three orders of magnitude (mean values of aquifer types) is evident.

Transmissivity values calculated by re-interpretation of pumping tests on individual boreholes are also present in all categories proposed by Krásný (1986, 1993) classification (Table 3.3). Here, 97% of individually calculated transmissivities are within the first four categories (I. to IV.), while only one aquifer type belongs to the first transmissivity category and two "least permeable" aquifer types are found in the category V. Absolute majority of aquifer types (97%) is classified within three categories (II. to IV.), while the any of delineated aquifer types is found in the last three categories (VI. to VIII.). Also the mean aquifer transmissivity values are distributed within not more than three orders of magnitude.

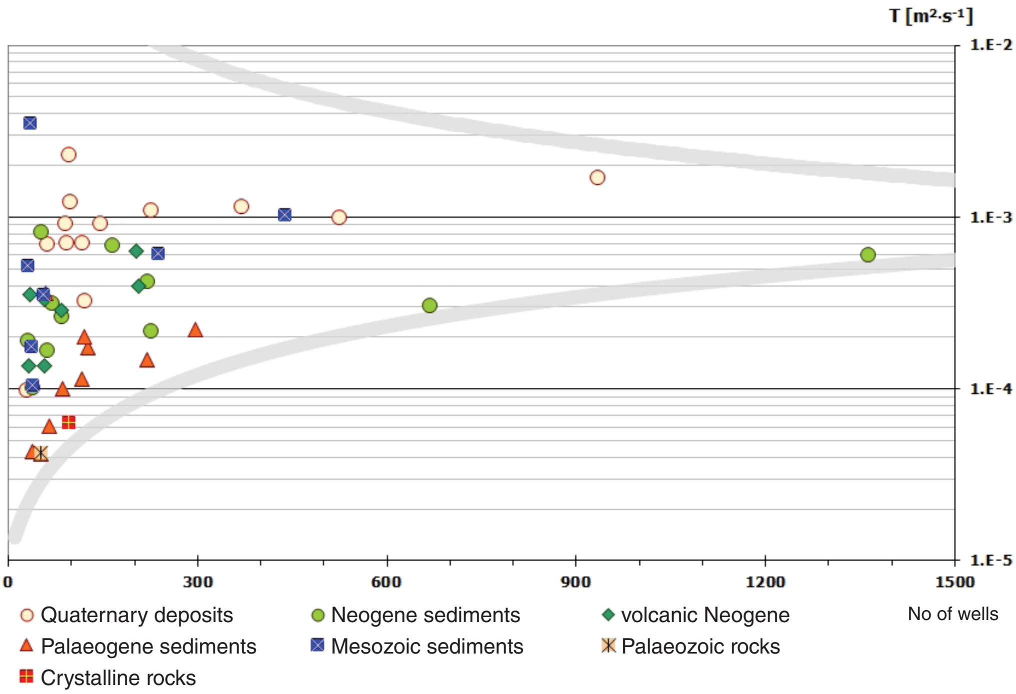


Fig. 3.23 Comparison of mean regional transmissivity values for aquifer types with ≥ 30 evaluated pumping tests on boreholes and wells.

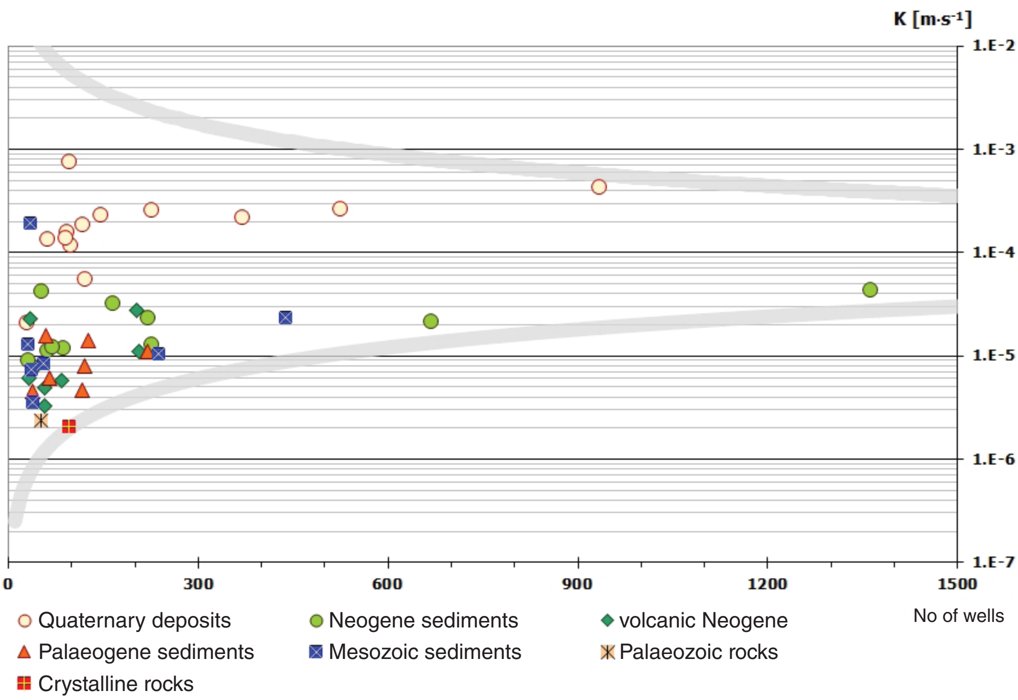


Fig. 3.24 Comparison of mean regional hydraulic conductivity values for aquifer types with ≥ 30 evaluated pumping tests on boreholes and wells.

As already found for pre-Quaternary aquifers (Malík & Švasta 2013), with the growing population of evaluated boreholes, the mean regional values of all (although lithologically, stratigraphically different) aquifer types are asymptotically approaching a relatively narrow interval of mean transmissivity values, between approximately $1 \cdot 10^{-4} – 1 \cdot 10^{-3}$ $m^2 \cdot s^{-1}$, as demonstrated in Fig. 3.23. The same situation (Fig. 3.24) of asymptotic inclination of regional means of hydraulic conductivity into a relatively narrow (although wider than in the case of transmissivities) is also visible. Here, all the regional geometric means of aquifer hydraulic conductivity where more than 30 borehole test could be interpreted, are within the interval of $1 \cdot 10^{-6}$ – $1 \cdot 10^{-3}$ $m \cdot s^{-1}$, and with the increasing number of tests are projected into a narrower interval of approximately $2 \cdot 10^{-5}$ – $4 \cdot 10^{-4}$ $m \cdot s^{-1}$. According to this, more attention should be given to the ways of entire characterisation of hydraulic properties distribution on both local and regional level, as analysed e.g. by Jetel (1990). Patterns of their distribution within different rock environment (sedimentary, metamorphic, igneous…), prevailing trends of privileged flow routes formation and typical heterogeneity manifestations in various aquifer types should be investigated in more detail. Spatial representation of transmissivity and hydraulic conductivity in their local and regional variations should be studied for better understanding of hydraulic behaviour of different rock environments. Its cartographical expression in maps and digital information systems should be in the future developed as well.

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Slovak Geol. Mag., 16, 1 (2016), 94 – 117

4. A First Contribution on Thermodynamic Analysis and Classification of Geothermal Resources of the Western Carpathians (an Engineering Approach)

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Abstract: Up to date, identified prospective geothermal areas cover 34% of territory of the Slovak Republic. In a contrast to repeatedly reported basic production and wellbore characteristics, geothermal waters and geothermal resources have never been classified by operation or field thermodynamics. The paper gives a brief review on production and field enthalpy distribution, specific exergy and exergy rate capacity of available production and exploration wells, gives a complex hint on thermodynamic quality of geothermal resources by applying the specific exergy index studies, and, provides a brief review on operation parameters of sites currently online by definition of utilization and thermal efficiency and performance indexes such is the sustainable index and thermodynamic improvement potential. In general, geothermal plays of the Western Carpathians are of low quality (SExI < 0.05) and low flow enthalpy (h_{field} < 550 kJ.kg^{-1}) at depths below 1 500 m. There are moderate-enthalpy and moderate-low exergy resources within the Danube Basin Central Depression (Čiližská Radvaň, Topoľovec, Veľký Meder, Topoľníky area), the Košice Basin (the Ďurkov area) and the Upper Nitra Basin (the Koš-Laskár area). If operation and performance indices are stacked, sites of the Tvrdošovce, Čiližská Radvaň, Chalmová, Koš-Laskár, Oravice, Podhájska and Bešeňová appear most adequate for onward development. This must, however, compromise sustainability, technical, social and economical aspects of use.

Key words: classification, geothermal resources, Western Carpathians, exergy, enthalpy, efficiency

4.1. Introduction

Geothermal energy is reported as renewable and sustainable. Natural renewability of geothermal resources is well held by reversibility in its thermodynamics at natural conditions and equilibrium between a source and its surroundings. Yet the sustainability is an artificial aspect of utilization of geothermal resources (Axelsson et al., 2004), requiring account on a certain irreversibilities in its exploitation and processing (Ozgener et al., 2007). A praxis has shown the temperature alone may be of use in particular description of natural conditions in which geothermal resources exist, however, lacks consistency in targeting quality of resources for use (Lee, 2001). Indeed, while temperature is not a conservative attribute and is destructed, e.g. during invasion of geothermal waters into shallower positions, enthalpy remains conserved in a reactive system or, at least, responses much slower (Fournier & Truesdell, 1974).

Geothermal resources have been classified by wellhead temperature (e.g. Franko, 1985; Fendek et al., 2011) or heat flow density – geothermic activity (Čermák & Hurtig, 1979). Still, numerous well established classification schemes, e.g. by play-type (Moeck, 2014; Moeck & Beardsmore, 2014), geothermal resource reporting method (Badgett et al., 2016; Garchar et al., 2016) or exergy (Lee, 1996, 2001) are missing in national source evaluation and analysis concepts.

A systematic exploration and research of geothermal resources dates for almost five decades in Slovakia. Recently, 27 prospective areas have been reported currently, covering 34% of a national territory with a total installed capacity of 149 MWt summarized at 56 sites online (Fendek & Fendeková, 2015). Amongst them, recreational sector owes a fair majority with 87.7 MWt (59%) ahead of agriculture (27.3 MWt / ≈ 18%), individual space (16.6 MWt / ≈ 11%) and district (16.2 MWt / ≈ 11%) heating, or ground heat pumps installations (1.6 MWt). In total, this represents roughly 39% of gross thermal installed capacity within all perspective areas or 2.2% of the total thermal potential. At the national energy mix, heat production from geothermal resources contributed with 5% (2 185 TJ) on total heat generation in 2014. According to Directive 2009/28/EC of the European Parliament and the Council on the promotion of use of energy from renewable sources, the country is called to increase a share of renewables up to 14% on a primary energy mix. Geothermal resources are identified amongst those of the greatest reliance in achieving the goal. With a term drawn in, an onward research and development in geothermal energy should then call on a definition of most perspective areas for high demand installations, identification of sites available for production improvements and sites of potential enough to increase utilization efficiency of current heat generation (e.g. by introducing cascade systems, optimization etc.).

Obviously, a desired increase in utilization of geothermal resources requires initiation of systematic, thermodynamic approach in evaluation and classification of geothermal waters and sites. The submission provides a first systematic overview on thermodynamics and geothermal waters quality in a region of the Western Carpathians.

4.2. REVIEW ON REGIONAL HYDROGEOTHERMICS

Current geological settings of the Western Carpathians owe to multiple folding and thrusting evolution through the Palaeozoic – Recent. A crystalline basement was formed through the Variscan orogeny achieving a crustal-nappe arrangement. Triassic carbonates-dominated sequences, deposited in variously differentiated promontories, underwent a nappe-thrusting in Early to Mid Cretaceous. In Palaeocene – Eocene, siliciclastics-dominates succession deposited onto broken and weathered pre-Tertiary relief. Through the Oligocene – Recent period, several episodes of tectonic dissegmentation and formation of intramountain depressions occurred as well as deep Neogene sedimentary basins were formed, intruded with volcanites. Carpathian depressions and basins are, in addition, covered with Quaternary accumulations of minor fresh-water carbonates occurrence.

4.2.1. Geothermal field and geothermic activity

Geological settings and global tectonic position, which is a reflection on geodynamic evolution, define anisotropy in distribution of a geothermal field of the Western Carpathians. In vertical distribution, (Franko et al., 1986) concluded the geothermal field and heat propagation up to ≈ 3,000 m is disturbed by morphology, water circulation and lithology, whilst at greater depths, the geothermal field is controlled at asthenosphere upwelling and crustal thinning or thickening tendency. A standardized mean heat flow density for the Western Carpathians has been calculated for 82 +/- 20 $mW.m^{-2}$, that characterizes a moderate to fairly increased geothermic activity. The heat flux (Fig. 4.1) increases (≈ 125 $mW.m^{-2}$) along Neogene volcanic propagation and thinned crust based basins. The activity distinctly decreases (50 – 85 $mW.m^{-2}$) at uplifted neotectonic blocks, intramountain depressions away of neovolcanic activities and areas of intense crustal thickening (Franko & Melioris, 2000). Compared to world average at 1,000 m (30 $°C.km^{-1}$), the geothermic gradient is quite increased in the Western Carpathians (38 $°C.km^{-1}$).

4.2.2. Geothermal play-types characteristics

A geothermal play-type is a model of how much a number of geological factors may generate recoverable geothermal resource at a specific structural position and certain geological setting (Moeck, 2014). By that, the play-type refers to drilling conditions, economics, resource characteristics, etc.

Let us neglect some concerns in basic systematics, confusing between geothermal fields and structures in identification of perspective areas, for a moment. Majority of localities refer to conduction-dominated, intracratonic basin (intramountain depressions) and foreland basin (Neogene sedimentary basins) plays (Moeck & Beardsmore, 2014). Intracratonic plays typically associate fault plane bound springs structures (e.g. Turiec depression), deep lateral leakage systems (e.g. Liptov Basin), basin constriction systems (e.g. Piešťany embayment) and bedrock high (e.g. Levoča Basin – W and S part) systems (Brook et al., 1987; Hochstein, 1988; Walker et al., 2005; Williams et al., 2008). Occurrence of reservoirs is controlled by existence of open fault tectonics and typical stratification of at least two Mesozoic nappe series beneath the Inner Western Carpathian Palaeogene (IWCP) or sedimentary Neogene fill. In Mesozoic formations, main aquifers are found in Mid Triassic carbonates. For Tertiary horizons, reservoirs associate with conglomerates and carbonates of the basal Borové Formation (IWCP) or sands and sandstones in Neogene, respectively. Geochemistry of geothermal waters varies due to longevity and depth of circulation, as they usually record carbonatogenic, transient and sulphatogenic, less (hydro)silicatogenic type. Degraded marinogenic waters are rather rare.

Foreland basin plays (Danube Basin Central Depression, Košice Basin, Vienna Basin) associate stratified sedimentary reservoir (Nathenson & Muffler, 1978) and bedrock (Williams et al., 2008) systems in major, however, towards peripheries, local fault plane-bound springs and lateral leakage systems (Brook et al., 1978) occur individually. Deep reservoirs in Mesozoic sequences (obviously Triassic) are often assumed only. Most of wells hit rather upper resources in Neogene sands and sandstones. Alike in previous, structures are usually semi-open or semi-closed and closed, respectively. Geochemistry of waters varies by reservoir depth, lithology and hydrogeological character of a system; however, marinogenic brines and degraded-marinogenic types are well documented.

Yet the Levoča Basin in its north-eastern part and the Humenné Ridge are affine to orogenic (basin) plays (Moeck – Beardsmore, 2014) owing stratified sedimentary reservoir systems (Williams et al., 2008) character. Reservoirs are rather buried deep in Triassic carbonates of various depths beneath flysch-type Palaeogene sequences, impermeable in essence. Geothermal waters are of silicatogenic to carbonatogenic or marinogenic-degraded types with obviously high TDS. Complexity in tectonics and vertical arrangement gives them a frequent semi-closed or closed character with minor recharge.

Some questions arise on a geothermal-play definition for Central Slovakian Neogene volcanites and the Beša--Čičarovce structure. In the first Neogene volcanites, deep-rooted magma channels intrude sedimentary Triassic to Neogene sequences, where majority of documented reservoirs occur; existence of geothermal resources in volcanoclastics is just rare yet. Even of apparently increased heat flow, we rather classify them as conduction-dominated intracratonic basin plays (Moeck, 2014), gaining stratified sedimentary reservoir to lateral leaking systems character (Nathenson & Muffler, 1978; Williams et al., 2008). Accumulation and flow of geothermal waters is controlled by open tectonics and superposition of caprock in Neogene volcanosedimentary complexes. This is a control of hydrogeological regime as well. The chemistry reflects actual host lithology and filtration characteristics, usually acquiring carbonatogenic to sulphatogenic, lesser (hydro)silicatogenic type.

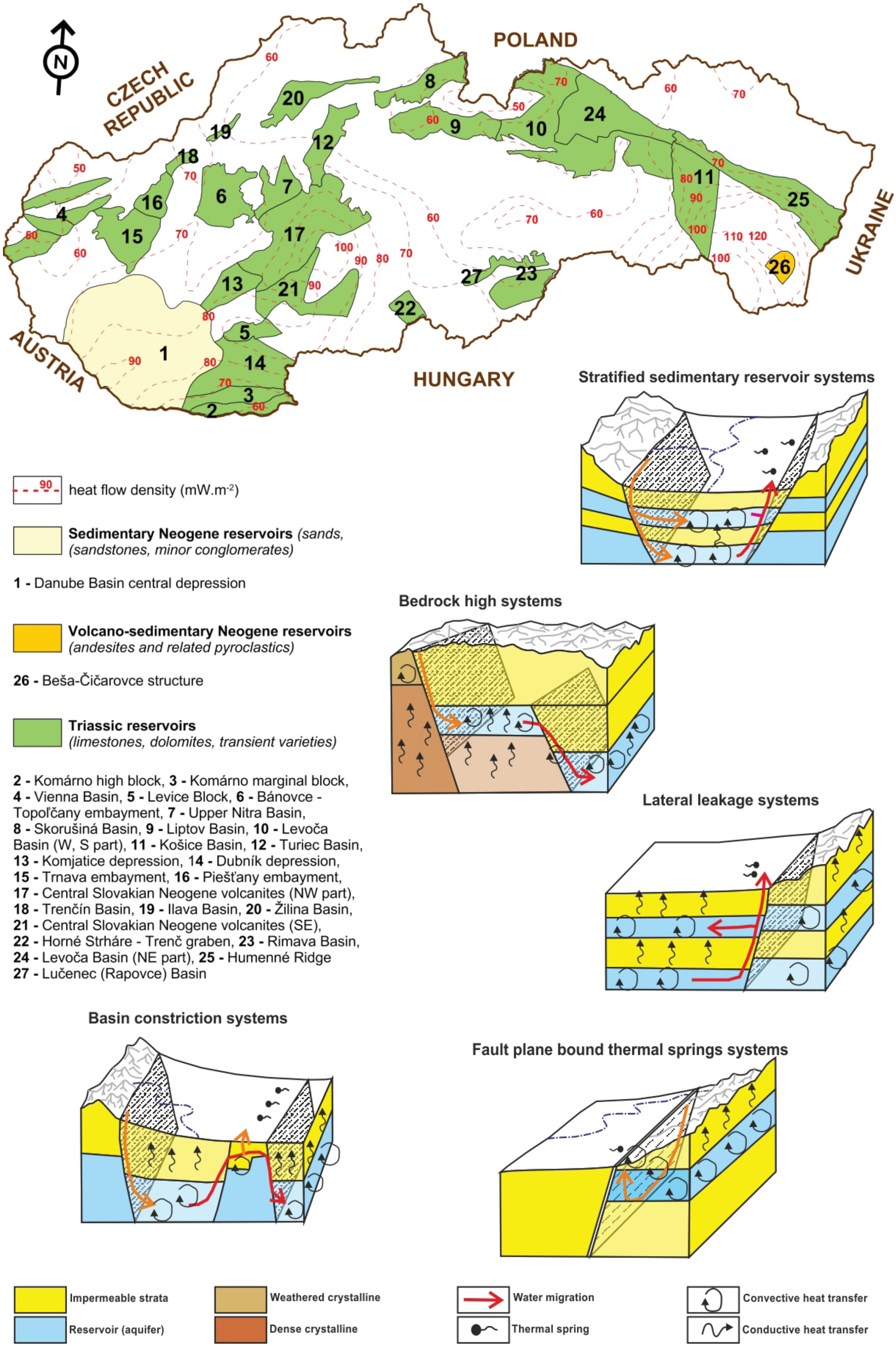

Fig. 4.1 Geothermal resources of Slovakia: prospective geothermal areas, heat flow density map and generalized play-type conceptions in regional conditions on reservoir stratigraphy background.

The Beša-Čičarovce structure represents a deep buried Neogene volcano in Neogene sedimentary fill of the Eastern Slovakian Basin, documented by geophysics and increased heat flow density at a surface. Occurrence of reservoirs is expected in Neogene andesites and related pyroclastics, thus the geothermal structure should be classified as conduction-dominated, foreland basin play (Moeck & Beardsmore, 2014) of stratified regional sedimentary reservoir character (Nathenson & Muffler, 1978). However, as there is a geothermal resource in volcanic products, the structure could be approached as convection-dominated, intrusive magmatic play-type (Moeck, 2014). At whatever position, we expect the structure to preserve a semi-closed or closed character, associating geothermal waters of marinogenic to degraded-marinogenic origin at high dissolved solids content.

4.3. APPROACH

4.3.1. A concept of thermodynamic quality

In natural conditions, the renewability of a geothermal resource, at least in terms of heat and mass delivery, links well with thermodynamic equilibrium, assuming the source is a closed or pseudo-steady-state system. According to the 1st Law of Thermodynamics, energy in natural systems is a conservative measure (1; subchapter 4.3.3.), thus the total energy balance applies, later described by a flow enthalpy (2) once either kinetic and potential energies, a heat and work transfers are neglected (Ozgener et al., 2005) due to equality.

The geothermal resource behaves no more as a (pseudo) closed system under artificial production and cannot be described by the energy balance as each change in initial thermodynamic conditions destructs achieved equilibrium. This is asserted by application of 2nd Law of Thermodynamics that accounts on entropy (thermodynamic disorder) creation (3). Then, the measure of energy available for any artificial conversion (e.g. work, heat delivery) is denoted as exergy (4), which is reciprocal to entropy generation, rather consumed or destroyed instead of being conserved, due to irreversibilities in real processes (Ozgener et al., 2007). For a given geothermal water at a specified flow rate and temperature, the specific exergy (4) transforms to a flow exergy or exergy rate (5) consequently balanced (6).

A problem of definition points

Both (4) and (5) require identification of appropriate definition points. Because of artificial use, the definition point s.s. refers to thermodynamic conditions at a wellhead or inlet into a conversion system, as this is a first stage the fluid is available to perform any work or heat delivery (DiPippo, 2005). Yet numerous studies accent a variation in exergy (and derived efficiencies) with a reference point (e.g. Ozgener et al., 2006; Utlu & Hepbasli, 2008; Kecebas, 2013). The dead-state s.s. addresses an environment of a source at zero working potential, that is unable to undergo any spontaneous change as it is in a complex equilibrium (Bodvarsson & Edgers, 1972; Bodvarsson, 1974). For realistic conditions, the reference state is often termed a restricted-dead-state (Lee, 1996), defined at sink or ambient p-T conditions.

Conversion efficiencies and potential

By the 1st Law of Thermodynamics, the energy efficiency (η – eta) defines how much of a heat conveyed is transformed into a heat production at a conversion stage (7) and sights on energy emission reductions regardless of its quality and origin. The 2nd Law of Thermodynamics screens irreversibilities in conversion processes (8) by exergy efficiency (ε – epsilon) or defines a quality rate the source is ready to deliver (Dincer & Rosen, 2013).

Apparently, the maximum exergy efficiency is achieved by minimizing differences between an input and output. An exergetic improvement potential is as follows (9). A rate of sustainability becomes proportional to efficiency in a conversion system (Gungor et al., 2011) or available energy the source can deliver to the process operated at current state (10).

4.3.2. A concept of thermodynamic classification and analysis

There are several classifications of geothermal resources by enthalpy (Bodvarsson, 1964; Nicholson, 1993; Axelsson & Gunlaugsson, 2000) basically defining low enthalpy fluids of up to 1,000 $kJ.kg^{-1}$ corresponding to 150 – 190 ˚C, depending on p-T, density and steam fraction saturation conditions. These grades are rather convenient with natural (initial) state conditions.

In reservoir engineering and geothermal field research and prospection, thermodynamic studies are conducted applying exergy and specific exergy index analysis in:

a) exergoeconomics, environmental and sustainability studies (Lozano & Valero, 1993; Bilgen & Sarikaya, 2015);
b) optimization of geothermal power plants (DiPippo, 2004) and heat production installations (Ozgener et al., 2007), including heat pumps (Soltani et al., 2015);
c) evaluation of geothermal fields (Quijano, 2000; Lee, 2001); and
d) classification of geothermal resources (Etemoglu & Can, 2007; Barbacki, 2012).

SExI – the specific exergy index

Enthalpy itself cannot be used to describe qualitative properties of a fluid exploited for energy conversion. Thereof the specific exergy index (11) has been introduced (Lee, 1996), relating exergy of a specified fluid to the enthalpy of pure water saturated with steam at 303 °C and 9 MPa. At this setup, the index gives an estimation of real conversion potential of a producing source. For sites with multiple wells or fields, the enthalpy and entropy are rather weighted by a produced mass flow (12-13) to give a site SExI (14). The same procedure is available for time-series analysis and definition of critical utilization scenario.

SExI – classification and mapping

Instead of arbitrary temperature classification guidelines derived off different geothermic conditions (e.g. Muffler & Cataldi, 1978; Hochstein, 1988), the concept of energy quality by SExI parameter refers to real thermodynamics of exploited fluids. In essence, (Lee, 1996, 2001) introduced two baselines. A limit of SExI = 0.5 refers to lowest exergy of saturated steam at p = 0.1 MPa and T = 100 °C, critical for high-scale and efficient direct power production, recorded in moderate-enthalpy to high enthalpy, double-phase or dry-steam fields. A limit of SExI = 0.05 describes a quality of saturated water at T = 100 °C and p = 1 Bar-abs, essential for low-scale, rather indirect (binary) power production or high-duty heat generation, typical for most of low enthalpy, single-phase, liquid-dominated fields. Then, the SExI = 0.2 describes a p-T conditions of double-phase natural systems at p = 20 Bar-abs at enthalpy over 1,000 $kJ.kg^{-1}$ (moderate / high enthalpy fields).

With baselines set, geothermal resources may be classified as follows:

a) low quality (exergy) resources or fields, SExI < 0.05;
b) moderate-low quality (exergy) resources or fields, 0.05 ≤ SExI ≤ 0.2;
c) moderate-high quality (exergy) resources or fields, 0.2 ≤ SExI ≤ 0.5;
d) high quality (exergy) resources or fields SExI > 0.5.

Besides technical quantification, geothermal resources or fields may be mapped using the enthalpy – entropy – pressure Mollier's or exergy – entropy – pressure Rant's diagram

4.3.3. Equations and symbols

$$\dot{Q}_{in} - \dot{Q}_{out} + \sum \dot{m}_{in} \cdot h_{in} = \dot{W}_{out} - \dot{W}_{in} + \sum \dot{m}_{out} \cdot h_{out} \quad (1)$$

$$\sum \dot{m}_{in} \cdot h_{in} = \sum \dot{m}_{out} \cdot h_{out} \quad (2)$$

$$s = -\oint (\delta Q / T) \quad (3)$$

$$e = (h - h_0) - T_0 \cdot (s - s_0) \quad (4)$$

$$\dot{Ex} = \dot{m}[(h - h_0) - T_0 \cdot (s - s_0)] \quad (5)$$

$$Ex = Ex_{heat} - Ex_{mass-in} - Ex_{mass-out} \quad (6)$$

$$\eta_{th} = \dot{E}_{out} / \dot{E}_{in} \quad (7)$$

$$\varepsilon_{ut} = \dot{Ex}_{out} / \dot{Ex}_{in} \quad (8)$$

$$IP = (1 - \varepsilon_{ut}) \cdot (\dot{Ex}_{in} - \dot{Ex}_{in}) \quad (9)$$

$$SI = 1/(1 - \varepsilon_{ut}) \quad (10)$$

$$SExI = (h - 273{,}15 \cdot s)/1192 \quad (11)$$

$$h_{field} = \left(\sum_i^n \dot{m}_{in} \cdot h_{in}\right) / \sum_i^n \dot{m}_{in} \quad (12)$$

$$s_{field} = \left(\sum_i^n \dot{m}_{in} \cdot s_{in}\right) / \sum_i^n \dot{m}_{in} \quad (13)$$

$$SExI_{field} = (h_{field} - 273{,}15 \cdot s_{field})/1192 \quad (14)$$

4.4. THERMODYNAMIC ANALYSIS

Since a systematic research and prospection on geothermal resources was launched in early 70's of the 20th Century, updates on evaluation of hydrogeothermal potential and prospection results have been reported repeatedly (Fendek et al., 1995; Fendek et al., 1999; Remšík, 2012; Fendek & Fendeková, 2010, 2015). Now there is a need to update results of geothermal exploration and research by basic engineering thermodynamics and basic indexes. This is because promotion and increase in geothermal energy use requires general knowledge on geothermal waters quality, recent state of utilization and capacity available at online sites or, at least, on potential left for onward improvements.

We have collected data from exploration and production wells installed in years of 1965 – 2015 (some basic attributes for most of them were already reported in Tab. 1 – Remšík, 2012), at least where essential attributes were available (yield / mass flow, wellhead temperature, total dissolved solids, reservoir stratigraphy, screened depth, geothermal potential, coordinates). Real production parameters (Fendek & Fendeková, 2015; Halás, 2015) have been taken for those wells installed, which report to the Slovak Hydrometeorological Institute as by Act No. 364/2004 Coll. on Water and later amendments. In a consequence, onward calculations may be skewed as much as how intense the uncertainties in reports are.

Together 133 wells were subjected to thermodynamic analysis. Derivation of enthalpy and entropy was carried by the REFPROP 9.0 (NIST), with following setup: reference substance – single compound substance, pure fluid – water (CAS number: 7732-18-5), specified state points – temperature (K) and density ($kg.m^{-3}$). This allows the REFPROP to calculate state points with limits to possible vapour formation and variation in thermodynamic properties by a fluid density according to critical point and reference properties (given by database; Wagner – Pruss, 2002) oscillation under specified ρ-p-T conditions.

4.4.1. Classification by enthalpy

Geothermal resources were documented in stratigraphic horizons dated through the Neogene to Mesozoic at screened (production) base intervals of 49 – 3,330 m. With a temperature varying 20 – 129 °C (293.15 – 402.15 K) at a wellhead and total dissolved solids (TDS) content of 400 – 90,000 $mg.l^{-1}$, the enthalpy of geothermal resources reaches 86 – 924 $kJ.kg^{-1}$. To classify geothermal resources, we have accepted a scheme by (Axelsson & Gunnlaugsson, 2000) with a cut-off level of 1,000 $kJ.kg^{-1}$ for high enthalpy resources, adjusted by an arbitrary value of 550 $kJ.kg^{-1}$ to delineate moderate-enthalpy resources assuming partial vapour fraction volatization at pressure greater than atmospheric (Truesdell & Fournier, 1977).

Stratigraphy criteria

Together 57 wells targeted a geothermal waters reservoir in sedimentary Neogene formations (sands, sandstones, conglomerates, clays) in the Danube Basin

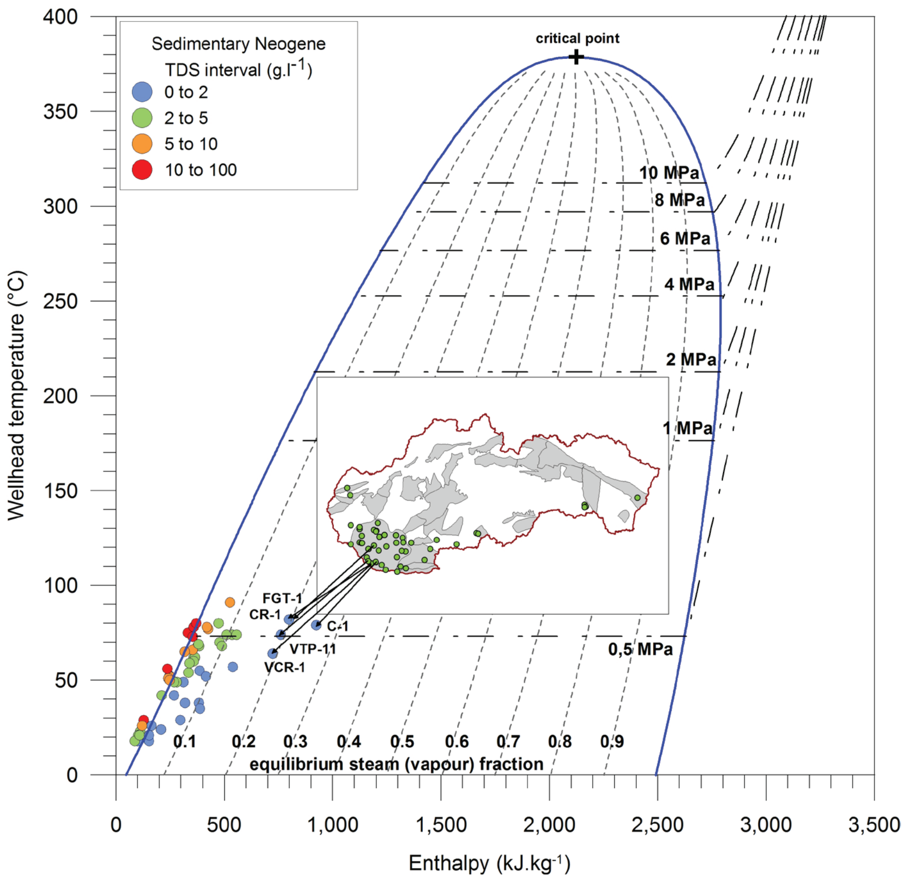

Fig. 4.2 Temperature – enthalpy diagram for geothermal waters of sedimentary Neogene

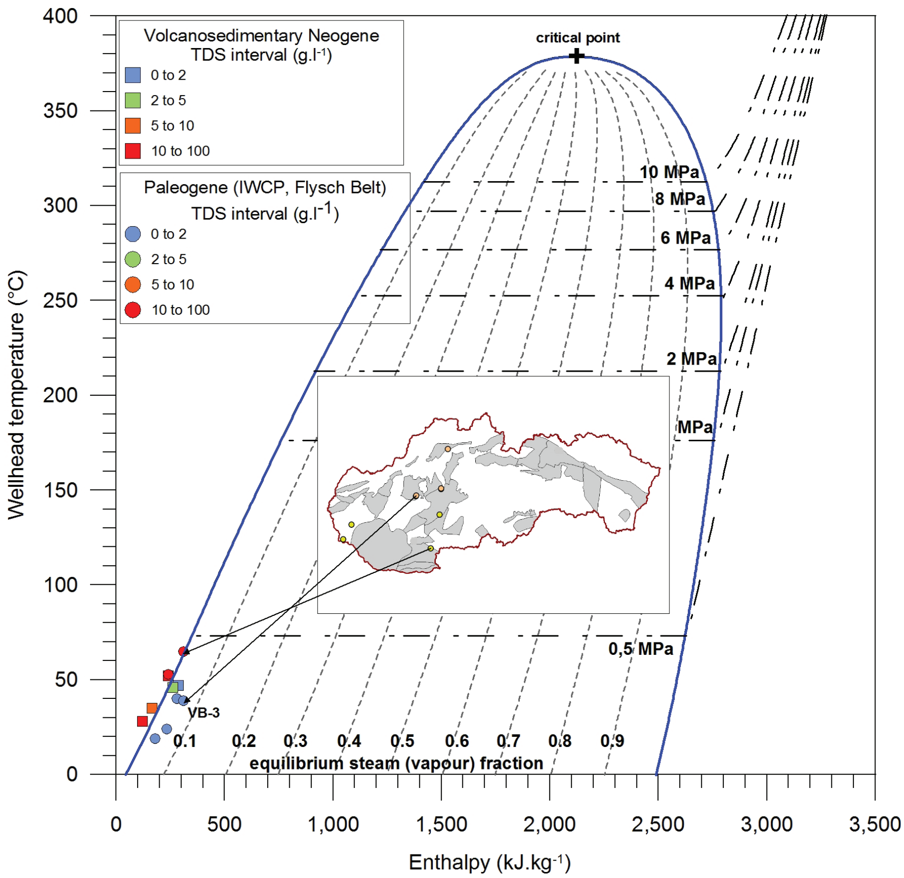

Fig. 4.3 Temperature – enthalpy diagram for geothermal waters of volcano-sedimentary Neogene and Palaeogene (IWCP, Flysch Belt) reservoirs

Central Depression (CDPP), Dubník Depression, Humenné Ridge, Horné Strháre-Trenč Graben, Komjatice Depression, Košice Basin, Komárno Marginal Block, Central Slovakian Neogene volcanites (SE part) and the at depths of 64 – 2,570 m. At the wellhead temperature oscillation between 20 – 91 ˚C (291 – 364 K) the TDS ranges through 400 – 90,000 mg.l^{-1}. The calcula-ted wellhead enthalpy reached h = 86 – 924 kJ.kg^{-1}.

Geothermal waters of the Č-1 Veľký Meder – Čalovo well can be described as of highest enthalpy due combining low TDS and T (h = 924 kJ.kg^{-1}, T_{wh} = 79 ˚C, TDS = 1,100 mg.l^{-1}, b_{perf} = 1,791 m). Moreover, geothermal waters at four wells can be considered of moderate enthalpy (ČR-1, VČR-16, VTP-11 and FGT-1). All are localized within the CDPP (Fig. 4.2, Tab. 4.1). Neogene reservoirs in other perspective areas are definitely of low-enthalpy, moreover, at questionable technological potential because of various TDS and yield.

Unlike for T_{wh} – b_{perf} correlation (R^2 = 0.88), the enthalpy does not necessarily increase with depth of reservoir (R^2 = 0.54) because of variation in TDS (Fig.4.2). At b_{perf} < 500 m and T_{wh} < 30 ˚C, the enthalpy difference is about 100 – 150 kJ.kg^{-1} for TDS = 500 – 12,000 mg.l^{-1}. An enthalpy reduction with TDS increases with depth. At depths of 1,500 – 2,000 m, the TDS = 900 – 90,000 mg.l^{-1}, whereas enthalpy of produced fluid at T_{wh} = 27 – 79 ˚C varies h = 250 – 950 kJ.kg^{-1}. Below 2,000 m, wells produce geothermal fluids at T_{wh} = 50 – 91 ˚C with TDS = 1,100 – 30,000 mg.l^{-1}. Here, highest enthalpies of h = 550 – 750 kJ.kg^{-1} were calculated for geothermal waters of TDS < 2,500 mg.l^{-1}. At the same depth, geothermal waters record lower enthalpies of h = 300 – 425 kJ.kg^{-1} at TDS > 5,000 mg.l^{-1}.

Volcano-sedimentary reservoirs are documented in the CDPP (FGB-1 Chorvátsky Grob, HGB-1 Rusovce), Dubník Depression (HGŽ-3 Želiezovce), and both parts in Central Slovakian Neogene volcanites (HR-1 Banská Štiavnica, R-3 Zlatno). Resources contain low enthalpy geothermal waters of h = 121 – 312 kJ.kg^{-1} at a wellhead temperature in a range of 28 – 69 ˚C and variable TDS content (2,000 – 19,200 mg.l^{-1}). Besides technological problems especially for Na-Cl type waters (e.g. GRP-1, HGB-1), volcano-sedimentary reservoirs are of low enthalpy potential and flow rate, in general.

Geothermal waters of the Levoča Basin (N part) were documented in PL-1 and PL-2 Plavnica wells, associated with Palaeogene sandstones and Triassic carbonates at depths of over 3,000 m, T_{wh} = 53 – 65 ˚C and TDS = 10,000 – 12,300 mg.l^{-1}. This is because of their marinogenic origin. Yet both wells associate well with volatile gases (CO_2, CH_4) causing incidental technical problems. Even of a great depth, both are of low enthalpy, h = 240 – 310 kJ.kg^{-1}. In comparison, MB-3 Malé Bielice and VB-3 Veľké Bielice wells (both within the Bánovce Embayment) produce geothermal waters of T_{wh} = 39 – 40 ˚C at a wellhead enthalpy h = 279 – 310 kJ.kg^{-1} under a production depth of up to 100 m from the IWCP horizons. Yet it is apparent that at a current state of exploration, the IWCP reservoirs contain low enthalpy fluids only.

Triassic geothermal waters were documented at 63 wells from 17 localities. Triassic carbonates are considered the most important reservoir formation in local conditions.

Alike in Neogene formations, temperature – enthalpy correlation in Triassic reservoirs increases (R^2 = 0.78) because of lower TDS content (400 – 31,000 mg.l^{-1}). Indeed, 71% of samples record a dissolved solids content below 5,000 mg.l^{-1}. This is because vast majority of structures are hydrogeologically open and intensively rewashed. Geothermal wells of T_{wh} = 20 – 129 ˚C (293 – 402 K) produce fluids from b_{perf} = 30 – 3,390 m. Marinogenic and degraded brines are observed only with the Košice Basin – Ďurkov area (GTD-1,2,3). Degraded and polygeneous brines were documented within the Levoča Basin – NE Part (L-1 Lipany) and the Komárno Marginal Block (M-1, M-3, GTM-1 Marcelová). In other structures, carbonatogenic to mixed waters prevail. Enthalpy in Triassic carbonates reaches h = 96 – 645 kJ.kg^{-1}. There is not any high enthalpy geothermal resource in Mesozoic strata. Four wells record possibility to produce moderate enthalpy (550 – 800 kJ.kg^{-1}) waters: GTD-1 Ďurkov (617 kJ.kg^{-1}), GTD-2 Ďurkov (645 kJ.kg^{-1}), GTD-3 Ďurkov (601 kJ.kg^{-1}) and Š-1-NB-II Koš (615 kJ.kg^{-1}). Another three wells, RTŠ-1 Kamenná Poruba (430 kJ.kg^{-1}), OZ-2 Oravice (433 kJ.kg^{-1}) and L-1 Lipany (442 kJ.kg^{-1}) produce geothermal water at enthalpy above a boiling point at atmospheric pressure. In general, Triassic geothermal waters may be, with listed exceptions, also considered as low enthalpy (Fig.4. 4).

At depths up to 500 m, geothermal waters from Triassic horizons produce enthalpy higher than those in Neogene reservoirs up to 100 – 250 kJ.kg^{-1}. By thermodynamics, it may be concluded that shallow Triassic reservoirs contain larger energy potential and "enthalpy hunting" approach may become more profitable, especially for low individual heating and small-scale agricultural and industrial heat processing (Fig.4. 5). The situation counters at depths over 1,000 m at even equal TDS content. Up to 2,500 m, highest enthalpies are documented for low TDS (< 5,000 mg.l^{-1}) geothermal waters produced from Pannonian – Pontian sands, this is, however, a general picture with exception of the Ďurkov wells and Š-1-NB-II in the Upper Nitra Basin. However, especially in Neogene horizons, the enthalpy hunting for high energy demand duties (individual or district heating, high demand heat processing for industry and agriculture) must compromise the absolute technical and processing potential of associated waters, where occurrence of mineralized brines (> 10,000 mg.l^{-1}) of (degraded) marinogenic brines increases with depths.

In conclusion, the vertical (stratigraphical) enthalpy distribution is consequent to:

- evasion of geothermal fluids from deep reservoirs into shallow positions and lower TDS content at depths up to 500 m ($h_{Tr2} > h_{Ng}$);
- frequent mixing between several horizons and continuous rewashing of reservoirs in Triassic carbonates due to frequent open hydrogeological regime ($h_{Tr2} < h_{Ng}$);
- association of Neogene reservoirs, especially those in CDPP with crustal thinning and extensive heat flow propagation ($h_{Tr2} < h_{Ng}$);

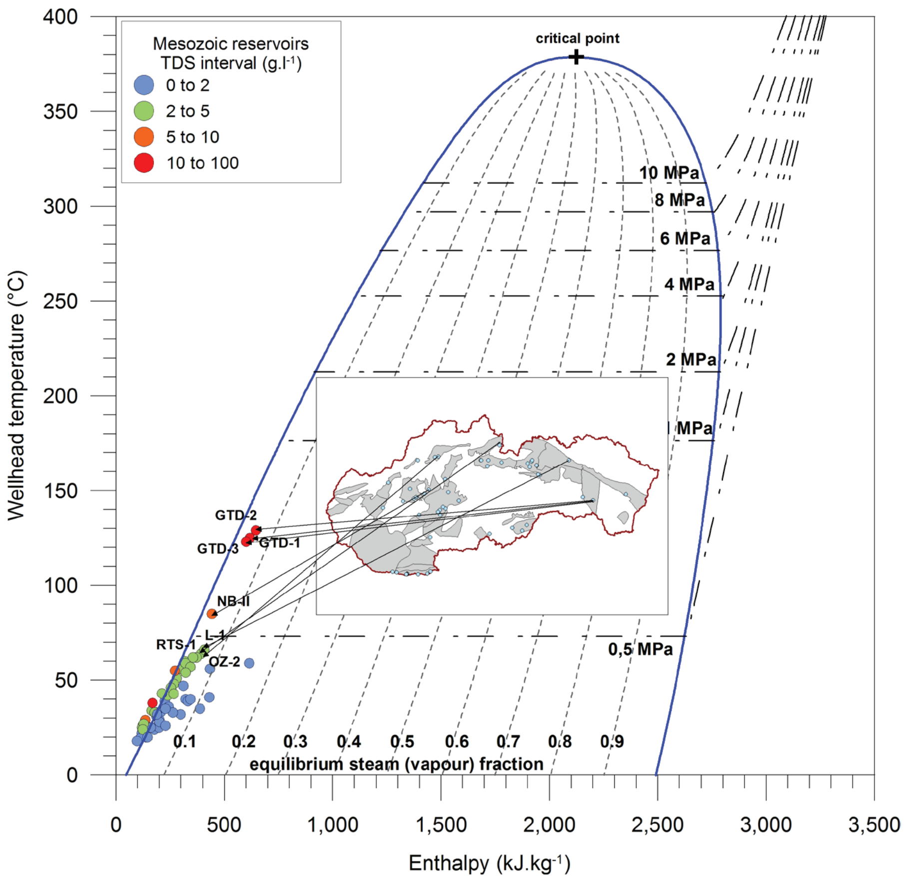

Fig. 4.4 Temperature – enthalpy diagram for geothermal waters of Triassic carbonates.

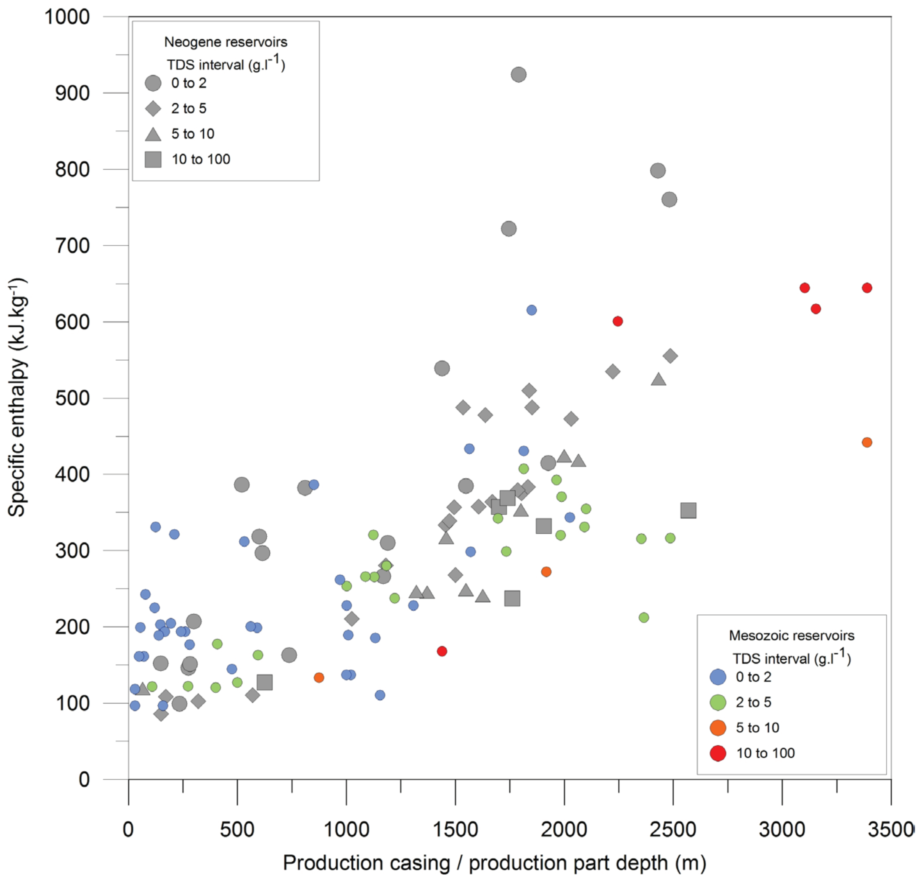

Fig. 4.5 Enthalpy distribution in the Western Carpathians with depth.

- extremely high TDS for marinogenic and degraded-marinogenic saline brines of Neogene at 1,500 – 2,500 mg.l^{-1} ($h_{Tr2} > h_{Ng}$ even at $T_{Tr2} < T_{Ng}$).

Prospective-area criteria

Up to this point, we have evaluated enthalpy conditions at individual wells. Description of identified prospective sites accounts on application of (12) to determine the field enthalpy per each locality. Given results are, however, skewed in some extension by

- productivity of installed wells;
- various TDS content;
- various reservoir depth and heterogeneous hydrogeological regime.

At general conditions, the enthalpy varies h_{field} = 120 – 610 kJ.kg^{-1} (Appendix A). The only area of moderate enthalpy (h_{field} = 610 kJ.kg^{-1}) is the Košice Basin. However, the Vienna Basin, Komjatice depression, Upper Nitra Basin, Turiec Basin, Liptov Basin, both parts of the Levoča Basin, Levice block, Dubník depression and the Skorušiná Basin exceed the average field enthalpy of the Western Carpathians ($h_{field-avg}$ = 281 kJ.kg^{-1}).

To reduce the skewing, we have normalized calculations by excluding wells of b_{perf} < 750 m, Q < 2 l.s^{-1} and TDS > 30 g^{-1}. After normalizing, the enthalpy varies h_{field} = 137 – 620 kJ.kg^{-1} (Appendix A). The Košice Basin appears in general the only area of moderate enthalpy. The Upper Nitra Basin and the Horné Strháre-Trenč Graben record enthalpy over 419 kJ.kg^{-1} for partial vapour formation at atmospheric pressure. The CDPP, Vienna Basin, Levoča Basin (NE), Levice block and the Skorušiná Basin exceed a regional enthalpy average ($h_{field-avg}$ = 328 kJ.kg^{-1}).

4.4.2. Exergy distribution

The enthalpy analysis is rather a qualitative measure of a heat (energy) content stored. Distribution and analysis of exergy is, instead, a study on possible real performance and energy quality potential available and deliverable from a reservoir to the production site. To provide a brief review on a situation in the Western Carpathians, we have examined both, the specific exergy (4) and the flow exergy or the exergy rate (5), understood as a thermodynamic quality contained in the source and a real available energy conveyed, or available for conversion, respectively. By definition, the exergy distribution relies on a specified reference (dead-state) conditions. For following analysis, let us consider the restricted dead-state as representative, defined at a TDS representative to sink temperature at 10 °C (283,15 K).

Specific exergy analysis

By specific exergy, geothermal resources appear monotonous in a thermodynamic quality content of e < 20 kJ.kg^{-1} at depths below 1,500 m. The low quality homogeneity applies for geothermal waters regardless of reservoir stratigraphy and TDS. Deeper, Triassic reservoirs contain the specific exergy above an average (e_{avg} = 20 kJ.kg^{-1}) in the Liptov Basin (FGTB-1 and ZGL-1 Bešeňová), Skorušiná Basin (OZ-2), Levoča Basin (GVL-1 Veľká Lomnica and FGP-1 Stará Lesná), and the Komárno Marginal Block (FGK-1 Komárno). Geothermal wells in the Ďurkov area exceed e > 80 kJ.kg^{-1}, however, at a production depth up to 2,300 – 3,300 m (Appendix B). Geothermal waters of highest quality are distributed within the CDPP. Reservoirs with production depth base of 1,500 – 2,500 m and a wellhead TDS < 5,000 mg.l^{-1} contain a specific exergy e > 40 kJ.kg^{-1}. Geothermal wells in the Čiližská Radvaň, Topoľovec and the Veľký Meder area record highest quality, with specific exergy over 80 kJ.kg^{-1} (Appendix B).

Exergy rate (flow exergy) analysis

The exergy rate (Ex) is amongst criteria in decision making for high-scaled conversion projects or power production optimization, understood as somewhat a quantitative measure in terms of real conversion potential delivery. Obviously, the flow exergy relies significantly on a mass delivery to the definition point. Unlike for enthalpy, the TDS increases then a real amount of energy available by advective supply due to an extensive mass flow.

In gross analysis, the overall exergy rate varies Ex = 1.9 kW (FGS-1) to 200 MW (GTD-3). If wells of Ex < 0.1 MW are excluded, the mean exergy rate at documented wells is calculated for Ex = 8.57 MW in conditions of the Western Carpathians.

In total, 89 wells (Appendix B) record an exergy rate of Ex > 0.1 MW. Highest exergy rate is calculated for the Ďurkov area, where geothermal wells are available at Ex = 169 (GTD-2) – 200 (GTD-3) MW. The greatest score is consequence to combination in high brine flow rate (50 – 65 l.s^{-1}), TDS (30 – 31 g.l^{-1}) and a specific exergy (99 – 113 kJ.kg^{-1}). Sites of Ex > 1 MW are also found in the Podhájska area, Komjatice, Galanta, Horná Potôň, Vrbov, Bešeňová, Šaľa, Topoľníky or Oravice, etc.

Yet this is a thermodynamic quality measure, not a gross power potential, as the water cannot deliver an effective work into a power turbine. If calculated for power potential, recalculations should be done to correct for enthalpy of the vapour fraction and flow rate, turbine efficiency, inlet pressure, etc. In addition, a count on a real available work relies on definition of sink point (e.g. heat exchanger outlet) instead of restricted dead-state. Thus the exergy flow rate can point on perspective wells or sites available for high demand duties.

4.4.3. Specific Exergy Index analysis

The exergy analysis is rather a supportive tool and an engineering approach in analysis of geothermal resources, relying on multiple factors, hard to normalize at a regional scale. The specific exergy index (SExI) is, alike, beneficial in strict identification of definition point conditions, that is, at the wellhead, independent on a reference state. Instead of considering variable reference conditions, the SExI accounts on two independent thermodynamic properties (enthalpy and entropy) at measurable conditions. This makes the SExI a respected classification and decision-making tool gaining global credits (studies conducted in the USA, Iceland, New Zeeland, Japan, Turkey, Poland, Latin America countries, etc.).

SExI field (flow-based) analysis

As we stated in above, classification of prospective areas by enthalpy suffers off the horizontal and vertical variability in attributes of geothermal resources, somehow uprisen by hydrogeological conditions, local hydrogeothermics etc. A representative SExI (14) per field weights enthalpy (12) and entropy (13) by flow rates. In fact, the $SExI_{field}$ accounts then for a weighted average of a certain number of wells (14).

A field SExI analysis must necessarily be skewed by heterogeneity of the perspective areas (Fričovský et al., 2016). The overall SExI = 0.003 – 0.102. Concerning production from reservoirs with b_{perf} < 500, the SExI = 0.003 – 0.018, with highest values calculated for the Komárno High Block and the Central Slovakian Neogene volcanites (SExI = 0,018). This may be an effect of uprising waters into shallow position in Triassic profiles. Some convective / advective heat addition (by ascending geothermal springs or cooling magma channels) cannot be excluded. By example, the Štúrovo area is for a long known of warm springs.

We assume that a cooling effect of reservoir rewashing and recharge ceases at b_{perf} > 1,000 m. Still, by the flow SExI, prospective areas may be evaluated as low quality (Tab. 4.1, Appendix A) up to 1,500 m. At greater depths, the $SExI_{field}$ = 0.018 – 0.102 for the Western Carpathians. The Košice Basin ($SExI_{field}$ = 0.102), Danube Basin Central Depression ($SExI_{field}$ = 0.07) and the Upper Nitra Basin ($SExI_{field}$ = 0.07) record a moderate-low quality score. This is typical for single-phase, liquid-dominated fields in conductive geothermal plays (Fig.4. 6) and corresponds well with heat flow density distribution and additional heat propagation by Neogene volcanism or crustal thinning. This may, however, decrease dramatically towards peripheries of identified localities. Given scores are calculated under given (known) attributes of produced geothermal waters and may vary with exploring of deeper reservoirs or drilling towards centres of geothermal plays where highest temperatures occur typically (Fig.4.7).

From a global perspective, moderate-low quality geothermal fields (Košice Basin, Upper Nitra Basin, Danube Basin Central Depression) record a similar quality to the well utilized low to intermediate enthalpy, single-phase, liquid-dominated systems, where e.g. Fuzhou (SE China) is exploited for large scale agriculture projects and ISH (Pang et al., 2015), the Balcova field (Turkey) supports a largest geothermal district heating system in Turkey (Ozgener et al., 2006), and the Tianjin (Tanggu) field is as well optimized for large scale geothermal district heating use (Axelsson & Dong, 1998). By similarity, it is apparent that at least those three structures could be of a service for district heating supply on a large scale (some projects are already online in the Veľký Meder, Galanta, Šaľa, Sereď).

SExI individual (borehole-based) analysis

For a borehole-based SExI analysis we have substitute individual enthalpy and entropy calculated at a definition point (wellhead) at each well (11). Obtained results are not skewed by weighting inputs with a flow rate.

Tab. 4.1 Review on thermodynamic quality of geothermal resources (field analysis)

Geothermal water body / number		$SExI_{field}$ / quality		$SExI_{field}$ / quality	
< 1.5 km			> 1.5 km		
Danube Basin Central Depression	SK300240PF	0.044-0.045	low	0.049-0.07	moderate
Komárno Marginal Block	SK300020FK	0.018	low	0.018	low
Komárno High Block	SK300010FK	0.05	low	n/a	n/a
Central Slovakian Neogene volcanites – NW part	SK300190FK	0.022-0.033	low	0.033	low
Central Slovakian Neogene volcanites – NE part	SK300200FK	0.02	low	n/a	n/a
Vienna Basin	SK300030FK	n/a	n/a	0.045	low
Trnava embayment	SK300040FK	n/a	n/a	n/a	n/a
Piešťany embayment	SK300050FK	0.004	low	n/a	n/a
Komjatice Depression	SK300180FK	n/a	n/a	0.039	low
Upper Nitra Basin	SK300100FK	0.048	low	0.07	moderate
Trenčín Basin	SK300060FK	n/a	n/a	n/a	n/a
Ilava Basin	SK300070FK	n/a	n/a	n/a	n/a
Žilina Basin	SK300080FK	0.019	low	0.038	low
Topoľčany - Bánovce embayment	SK300090FK	0.023-0.025	low	0.025-0.028	low
Turiec Basin	SK300110FK	0.029	low	n/a	n/a
Skorušina Basin	SK300120FK	0.04-0.046	low	n/a	n/a
Liptov Basin	SK300130FK	0.024-0.032	low	0.024	low
Levoča Basin - W,S part	SK300140FK	0.028	low	0.032	low
Levoča Basin – NE part	SK300150FK	n/a	n/a	0.039	low
Humenné Ridge	SK300160FK	0.006	low	n/a	n/a
Košice Basin	SK300170FK	n/a	n/a	0.102	moderate
Levice Block	SK300210FK	0.037	low	0.04	low
Rimava Basin	SK300220FK	0.008-0.01	low	n/a	n/a
Beša - Čičarovce structure	SK300130FP	n/a	n/a	n/a	n/a
Dubník Depression	SK300250PF	0.032	low	0.034	low
Lučenec - Rakovce Basin	SK300220FK	0.009	low	n/a	n/a
Horné Strháre-Trenč Graben	SK300260FK	0.025	low	n/a	n/a

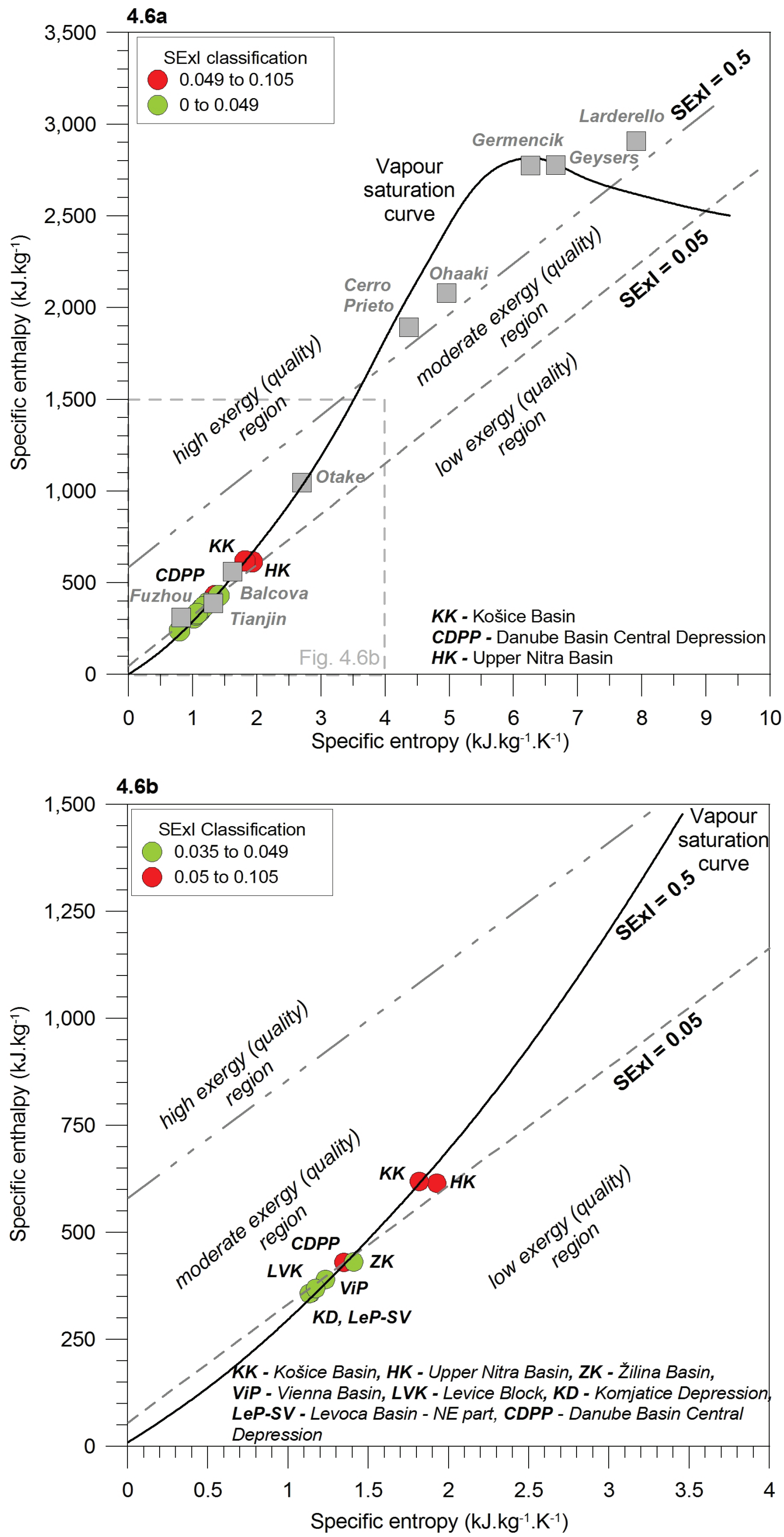

Fig. 4.6 Prospective geothermal localities map on a Mollier's diagram with perspective of global geothermal fields.

The approach is usually used for detailed analysis of geothermal systems or sites operating a single well.

In general, the average SExI is 0.029 as given off the range SExI = 0.0025 – 0.145. Under current state, geothermal resources may then be classified as low to moderate-low exergy. For wells with reservoir production depth of b_{perf} > 500 m, the average SExI = 0.035 at increased minimum limit to SExI = 0.0039.

Together 20 wells counted SExI > 0.05 and reached the moderate quality. Out of these, 13 are located in the Danube Basin Central Depression with the Veľký Meder, Čiližská Radvaň, Topoľovec, Topoľníky, Galanta, Vlčany, Diakovce, Dunajský Klátov or Zemianska Oľča areas (SExI = 0.051 – 0.145). In the Košice Basin, the SExI within the Ďurkov area counts 0.097 to 0.110. The highest SExI in the Upper Nitra Basin is calculated for the Koš

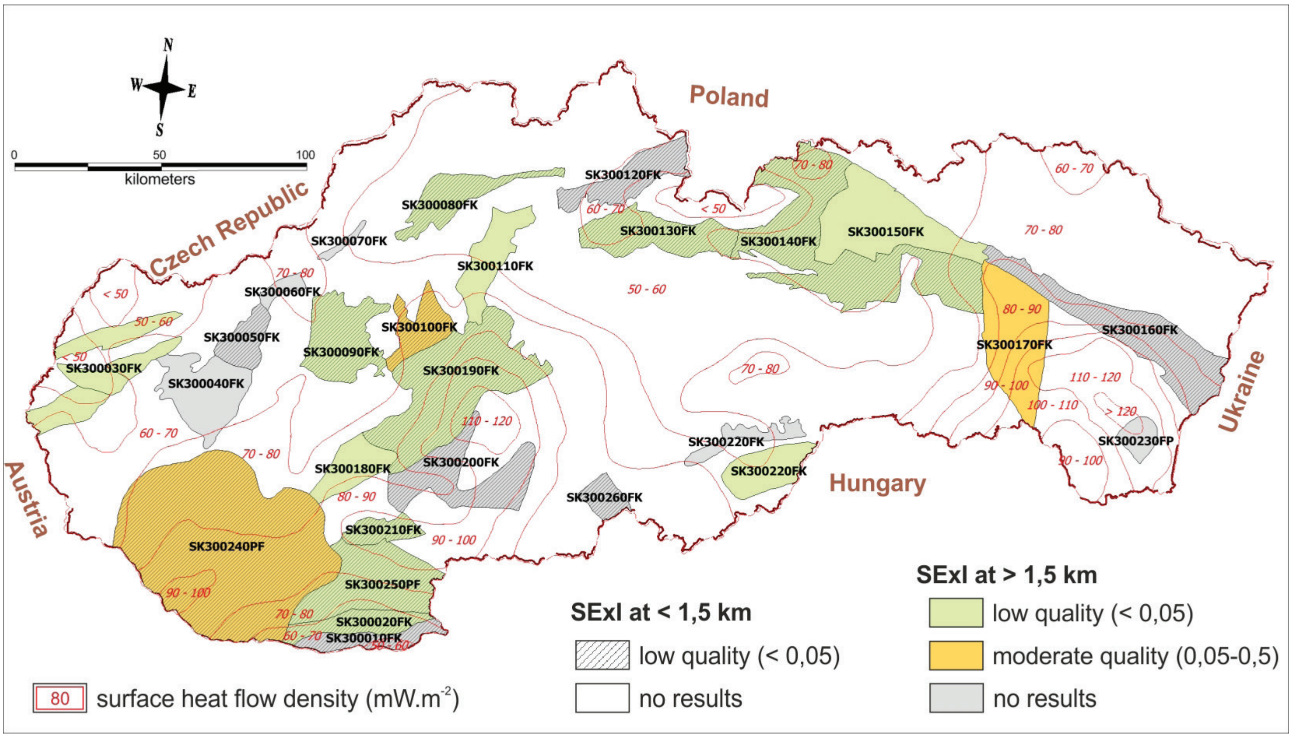

Fig. 4.7 Distribution of thermal waters thermodynamic quality with correlation to the heat flow density map (numerical indicators to geothermal water bodies).

– Laskár area (SExI = 0.074) documented for Š-1-NB-II well. Two other wells, L-1 Lipany (SExI = 0.0557) and RGL-1 Lakšárska Nová Ves (SExI = 0.0501) represent the highest quality for the Levoča Basin (NE part) and the Vienna Basin, respectively (Appendix B).

Evident distinctions between SExI level and reservoir stratigraphy are missing. Out of 57 wells in producing (or documenting) reservoirs in Neogene (SExI = 0.0025 – 0.145), vast majority (42) is up to SExI = 0.0425. The SExI produced from Triassic reservoirs counts 0.00308 (HM-5 Tornaľa) to 0.1107 (GTD-2 Ďurkov), however, 52 out of 62 wells yield the SExI score below 0.035.

A correlation of production part depth (b_{perf}) to the SExI ($R^2 = 0.44$) is questionable at a least. In fact, drilling deeper or producing deeper horizons does not necessarily mean an increase in thermodynamic quality of geothermal waters, which is conform to conclusions for enthalpy distribution in documented wells and reservoirs. Under regional conditions, the relation of SExI with produced temperature is rather exponential ($R^2 = 0.85$) as the enthalpy and entropy are a function of not only a temperature, but a pressure and TDS as well. Then, there is a clear difference between the installed geothermal potential and a quality of a geothermal water (Fig.4.8).

We see now that the individual SExI may be considerably higher than that analysed per geothermal fields or sites. For example, the flow SExI for the CDPP has been calculated for $SExI_{field} = 0.044 – 0.07$, the SExI of individual wells counts SExI > 0,1 for VTP-11 Topoľovec, ČR-1 Čiližská Radvaň and Č-1 Veľký Meder (Čalovo).

In a global perspective, geothermal resources of moderate-low quality (Fig.4. 9) are fairly similar again to those operated e.g. at the Balcova site, supplying a geothermal district heating system through the year, thus may definitely be utilized in high-demand duties.

The SExI alone is not a self-contained indicatory on a potential use. A praxis shows it is better to use the specific exergy index to analyse thermodynamic quality of particular site and then to search for a desired deliverability, according to a project the site should be designed for, or to update a project parameters. Along, a reservoir (site) sustainability and production compromises must be understood. In a meantime, the SExI itself does not account on potential risks associated with utilization of geothermal resources (i.e. the Ďurkov wells are of highest quality, but are known for a huge TDS and calcite to silica rapid scalings).

4.5. OPERATION OVERVIEW

4.5.1. Efficiency

As it was already stated, the Slovak Republic is called to increase a share of "renewables" on a national energy mix, including use of geothermal resources. In fact, the goal can be approached as: a) to search and develop new sites, b) to develop existing sites; and c) to increase an efficiency at existing sites. Under ideal economics, all must come together to maximize the effort. However, at some restricted scale, the easiest way is an increase in overall utilization efficiency. Options "a" and "b" must, however, compromise a sustainable use of geothermal resources, whilst increase in efficiency is rather an engineering issue on an operator's side.

Thermal efficiency

The thermal efficiency (η_{th}) is easily understood as a ratio of a heat produced to the heat abstracted (7), thus

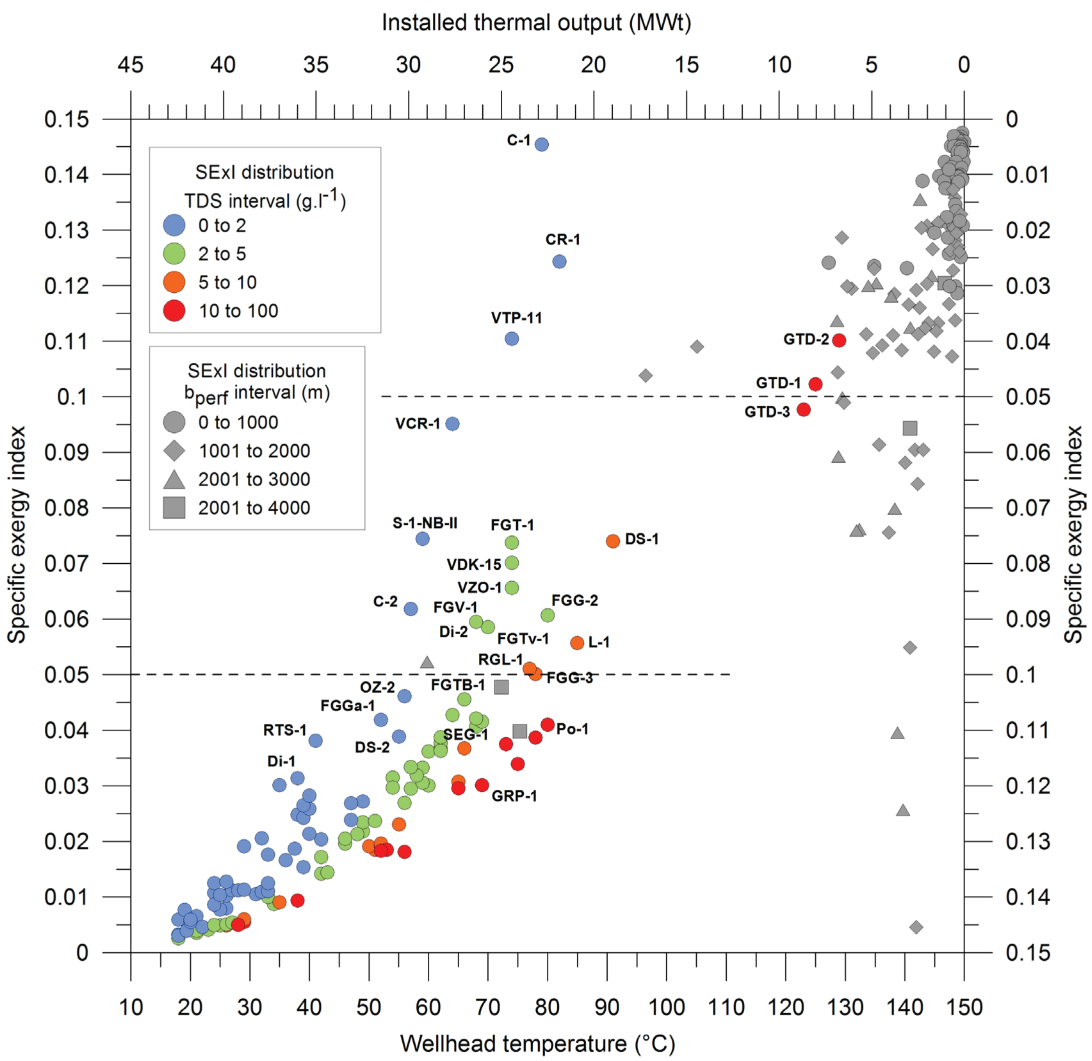

Fig. 4.8 Specific exergy index (SExI) relation to wellhead and installed thermal output

describes how much of a potential is consumed in a heating process (e.g. DiPippo, 2005). The thermal efficiency is amongst most important critical indexes in an engineering analysis of operated sites all along with the capacity factor (actual output in a period of time over an output if operated at a full time), availability factor (actual time of production over a full period of time) and a coefficient of performance (energy output over an electricity energy input to the ground source heat pump).

To provide a brief overview on a performance, we have taken actual reports of thermal output (Fendek & Fendeková, 2015) and compared them to the nameplate output – TTP (Remšík, 2012). The study has been conducted on 60 wells with complete data available.

Surprisingly, 15 wells are used at a full thermal efficiency (η_{th} = 1 or 100%). This is, however, a very unlikely case. At given data, the wells of FBe-1 Bešeňová, HGDS-1 Dolná Strehová, FGG-1 Galanta, BCH-3 Chalmová, FGO-1 Obid and SB-3 Patince are evaluated as of less installed thermal output than the actual output reported. Sites operating wells of BHS-3 Belušské Slatiny, Di-3 Diakovce, G-4 Košice, GN-1 Nesvady, PP-1 Poprad, KMV-1 Sielnica, GTŠ-1 Šaľa, HM-5 Tornaľa and HG-18 Vinice are evaluated to the same TTP as actual output. The high (let's say somehow unrealistic) efficiency may come consequent to erroneous reports or may give some hint of a hazardous use of a geothermal resource.

If we neglect those wells of η_{th} = 1, the thermal efficiency of online wells counts η_{th} = 0.03 – 0.98. With given data, 21 out of 45 wells utilize the resource with η_{th} > 0.75. By purpose, sites utilizing geothermal resource for balneology report a thermal efficiency of η_{th} = 0.03 – 0.98 (average efficiency counts η_{th} = 0.68). If reports are correct, there is a huge potential to increase an use of geothermal waters in the Oravice area (OZ-2: η_{th} = 0.03), Nové Zámky (GNZ-1: η_{th} = 0.08), Veľký Slavkov (VSČ-1: η_{th} = 0.14), Galanta (FGG-3: η_{th} = 0.23), Partizánske (FGTz-1: η_{th} = 0.41) or Šurany (GMŠ-1: η_{th} = 0.08). In agriculture, the thermal efficiency increases towards η_{th} = 0.38 – 0.97, at a mean of η_{th} = 0.71. The high efficiency is by coupling a drying, fish farming and greenhouse-heating with high-demand use, such as individual heating (e.g. TTŠ-1 Turčianske Teplice; η_{th} = 0.92), or recreation purposes (e.g. FGČ-1 Čilistov; η_{th} = 0.97). At individual use for agriculture, the thermal efficiency varies η_{th} = 0,38 – 0,75, at a mean of η_{th} = 0,66. Thermal efficiency of individual space heating (not-cascaded) is about η_{th} = 0.39 – 0.47 off the Koš-Laskár (Š-1-NB-II) and Chalmová (HCH-1). If sources

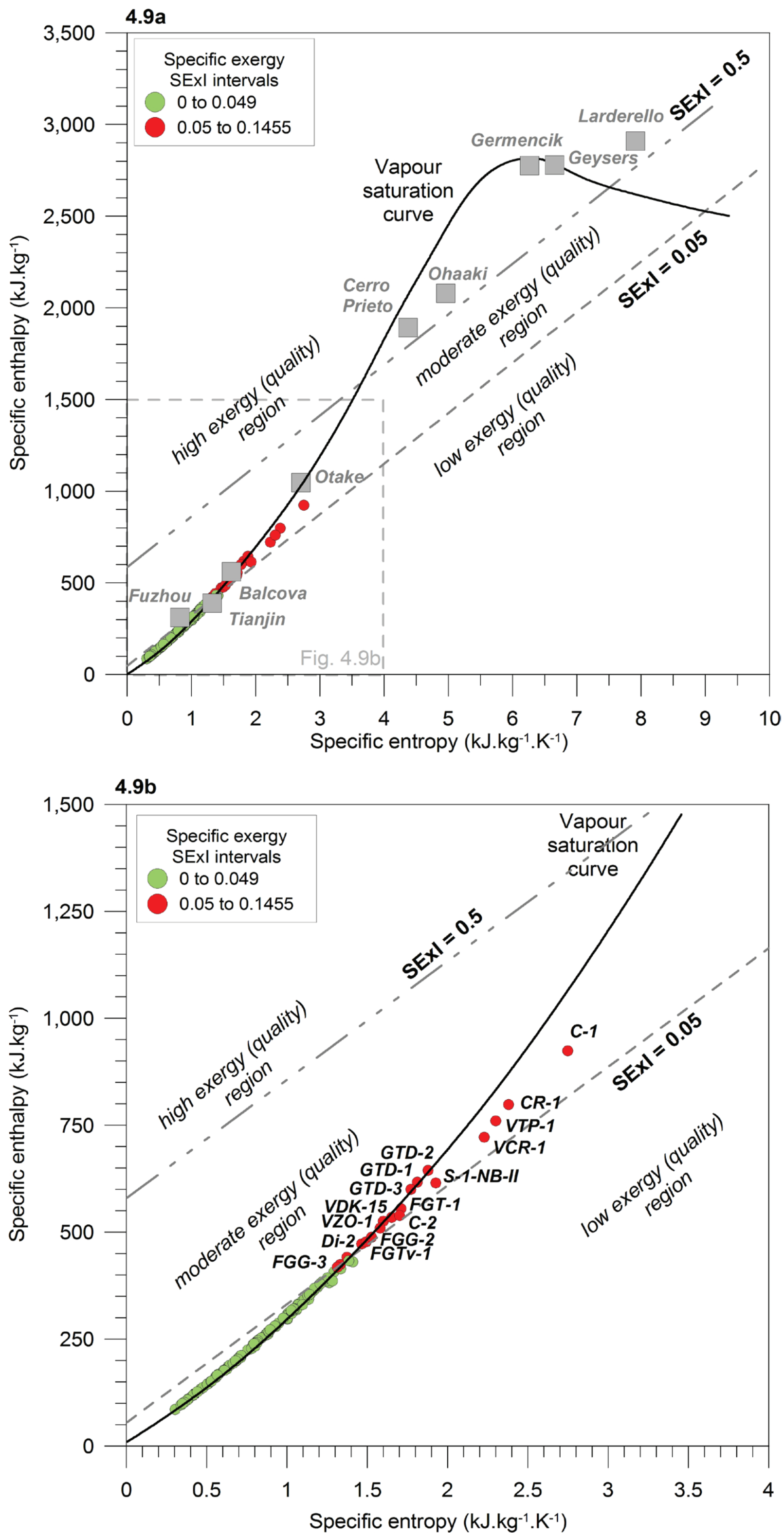

Fig. 4.9 Specific exergy distribution map on a Mollier's diagram in global (up) and detailed (down) perspective

are utilized in cascades, the thermal efficiency rises to $\eta_{th} = 0.03 - 0.95$. We may have pointed to some thermal potential available to increase at Oravice, Koš-Laskár, Chalmová, Vlčany or Bešeňová. Wells implemented into district heating network record a mean thermal efficiency of $\eta_{th} = 0.73 - 0.99$. Wells in Šaľa (GTŠ-1) and Galanta (FGG-1) are reported of $\eta_{th} = 1$, however, this has already been discussed above. A geothermal well of Sereď (SEG-1) operates at $\eta_{th} = 0.98$ in individual setup. Other sites are connected to cascades with recreation and individual space heating.

Thermodynamic (utilization) efficiency

The thermodynamic or utilization efficiency (ε_{ut}) answers rather on how the resource is utilized. With available data, we define the utilization efficiency by relating actually produced exergy rate (Ex_{out}) to the exergy rate available (Ex_{in}) under defined restricted dead-state (8). The produced exergy rate refers to sink conditions (T_{outlet}).

At operated sites, the utilization efficiency varies ε_{ut} = 0.04 – 0.94 with a mean of 0.56. Highest utilization efficiencies have been reached in the Nesvady (ε_{ut} = 0.94), Šaľa (GTŠ-1: ε_{ut} = 0.86) or Sereď (SEG-1: ε_{ut} = 0.86) area, where sink temperatures are of T_{outlet} = 12 – 15 °C. An efficiency of wells supplying recreational duties only is ε_{ut} = 0.04 – 0.84, at average of ε_{ut} = 0.49. Sites produced for agriculture record an efficiency of ε_{ut} = 0.42 – 0.94. Apparently, there is some considerable potential to increase in the Tvrdošovce (FGTv-1: ε_{ut} = 0.42) and the Čiližská Radvaň (ČR-1: ε_{ut} = 0.63) areas, where sink temperatures are about T_{outlet} = 20 °C and the thermal efficiency is kept below η_{th} = 0.75. Individual space heating as a single network is realized in the Koš-Laskár (ε_{ut} = 0.37) and Chalmová (ε_{ut} = 0.55) only. The Sereď (ε_{ut} = 0.85) and Šaľa (ε_{ut} = 0.86) areas are the only sites where geothermal water supplying a GDHS is not used for other cascaded duties.

We list all efficiencies of utilized geothermal wells in Appendix B. Obviously, both, the utilization (ε_{ut}) and thermal (η_{th}) efficiencies increase with a load or duty. While wells operated for individual purposes reach the annual mean efficiencies of counts η_{th} = 0.08 – 0.98 and ε_{ut} = 0.04 – 0.94, the utilization efficiency of cascaded systems increases, especially for a minimum limit to ε_{ut} = 0.2 – 0.84 with simultaneous increase in thermal efficiency for η_{th} = 0.06 – 0.97.

4.5.2. Improvement potential

Improvement in site operation is a compromise between economics, legal aspects, demand and available potential. Selection of possible sites is usually (amongst basic hydrogeothermal, socio-technical and sustainability studies) grounded by thermal and / or utilization efficiency analysis.

An improvement potential (IP) has been introduced as one of tools to effectively describe limits of operated sites for increasing their productivity. By definition (9), the IP increases with difference between potential (Ex_{in}) and operated (Ex_{out}) exergy. It is then useful in definition of sites where there can be some increase in heat extraction from a source by adopting of new technologies, or sites, where there is still temperature at outlet high enough for improvement. A clear disadvantage of the index is its reliability on initial, restricted dead-state conditions (which is the same problem as for exergy calculation).

We list the IP index of operated wells in Appendix A. By the IP, sites in Dunajská Streda (DS-1: IP = 1.44), Oravice (OZ-2: IP = 0.99), Galanta (FGG-3: IP = 1.09), Bešeňová (FGTB-1: IP = 0.60), Tvrdošovce (FGTv-1: IP = 0.91), or Podhájska (Po-1: IP = 11) appear available for improvement, as η_{th} < 0.70; ε_{ut} < 0.70; T_{outlet} > 25 °C. This is, however, an informative parameter requiring detailed exergetic and thermodynamic analysis.

The sustainability index (SI) relates the operation thermodynamics to sustainability (10). The greater is the utilization efficiency, the more energy is actually converted or consumed in a heat production, and, consequently, the less potential for additional "work" is available, increasing the sustainability index. By that, e.g. the Šaľa (FGŠ-1) and Sereď (SEG-1) sites of ε_{ut} > 0.8 and η_{th} > 0.8 give the SI > 7. At these sites, the potential to increase the heat production is significantly lower. In the contrast, the FGG-3 well in Galanta operates at ε_{ut} > 0.7 and η_{th} < 0.5 with SI = 2.55.

4.6. Summary

The territory of the Western Carpathians (Slovakia) has been repeatedly described by temperature or a heat flow distribution. More than 160 exploration and production wells were subjected for temperature or heat flux measurements, tested for a balanced yield or evaluated towards definition of nameplate thermal output (total thermal capacity). Still a general review on explored (and recently available) geothermal resources lacks reports on sustainable reservoir management studies and production thermodynamics.

Geothermal play-types of the Western Carpathians may generally be classified as low-enthalpy where a field enthalpy becomes 137-620 $kJ.kg^{-1}$. The only exception is the Košice Basin, where the field enthalpy in the Ďurkov area consistently exceeds a limit condition of h = 550 $kJ.kg^{-1}$ delineating moderate enthalpy resources. The Danube Basin Central Depression, Vienna Basin, Levoča Basin (NE), Levice Block, Upper Nitra Basin, Horné Strháre-Trenč Graben and the Skorušiná Basin exceed a regional enthalpy average (h_{field} = 328 $kJ.kg^{-1}$). A production enthalpy varies 86 – 924 $kJ.kg^{-1}$. Moderate enthalpy geothermal waters are currently documented in the Ďurkov area, Koš-Laskár, Čiližská Radvaň or Topoľníky, because of sensitivity of enthalpy to TDS possible to skew differences in wellhead temperature. These are the only wells exceeding a specific exergy of e > 70 $kJ.kg^{-1}$ at a regional average of e = 20 $kJ.kg^{-1}$. Under given geothermics and current state of exploration, geothermal plays of the Western Carpathians are all low-quality while reservoir production depth up to 1,500 m. At greater depths, the CDPP, the Košice Basin and the Upper Nitra Basin appear of moderate-low quality, at least within most productive zones. By individual analysis, these sites include 20 wells in total of moderate-low SExI. An onward developing or a search for a new sites should follow an anomaly stacking approach (Cumming, 2009), targeting then shallow Triassic reservoirs for low-duty (recreational) use, whilst Neogene reservoirs at TDS < 2,500 $mg.l^{-1}$ and base at 1,500 – 3,000 m for a high-demand operation in, probably, most profitable scenario. There is, however, a question of deep Triassic reservoirs, available for a high demand use by a natural productivity of carbonates, even at lower thermodynamic quality. In addition, many sites produce geothermal waters from upper Triassic series (e.g. in the Liptov Basin), where existence of deeper, most probably closed reservoirs, cannot be excluded. Extended drilling is, however, a far-long run. Yet drilling deeper does not necessarily comes with higher enthalpy and thermodynamic qualities.

Previously, regional geodynamics, shallow geomorphology and groundwater circulation were concluded as crucial controls on hydrogeothermics of the Western Carpathians (Franko & Melioris, 2000). Reservoir thermodynamics, enthalpy and quality distribution are, moreover, controlled by a TDS content, palaeohydrogeology, formation productivity, and play-type.

By individual analysis, utilization and use indexes (IP, SI, η_{th}, ε_{ut}) increase well where coupled heat production is installed, the more for resources at higher temperature. In regional conditions, the thermal efficiency ranges $\eta_{th} = 0.03 – 0.98$. According to reported data, 21 out of 45 wells were calculated for a thermal efficiency $\eta_{th} > 0.75$. At operated sites, the utilization efficiency is with an interval of $\varepsilon_{ut} = 0.04 – 0.94$ at an average of $\varepsilon_{ut} = 0.56$. Stacking indexes onto (see calculations listed in Appendix B), selection of sites available for production development must then rather be a compromise of: thermal efficiency $\eta_{th} < 0.8$; utilization efficiency $\varepsilon_{ut} < 0.8$; improvement potential IP > 0.5; sustainability index SI < 5; and temperature outlet $T_{outlet} > 20$ ˚C to maintain a gradient between an exhaust and sink conditions. This is, however, only a thermodynamic, or energy potential approach. Obviously, the increase in a heat production at existing sites must simply come with operation economics and investments, demand, technology. Meanwhile, there is (often somewhat) a neglected aspect of reservoir thermal sustainability, which must necessarily be studied, or rather, which principles must simply be adapted into national legislative schemes.

4.4.7. Endnotes

It is a must to accent the conducted study is strictly limited to data available off decades of the research, prospection and development in the country while analysing production thermodynamics (enthalpy, specific exergy, exergy rate, exergy quality), as these are based on previously published input data (wellhead temperature, deliverability, reservoir production part depth, TDS, reservoir stratigraphy), with a last update presented (Remšík, 2012). Obviously, flow (field) analysis results may then vary with new results given by continuous drilling and exploration.

Operation analysis relates to reports given to the Slovak Hydrometeorological Institute as presented on a World Geothermal Congress 2015 (Fendek & Fendeková, 2015). We have already discussed some limitations listed above. Yet the site performance analysis gives an overview on average reported data. A more detailed approach is necessary, as performance indexes vary seasonally, thus a step-by-step time-domain studies must simply come in following. We recommend to use and accept presented data as a baseline.

Geothermal resources of the Western Carpathians may play an indisputable role in a primary energy mix of the country. Even already developed sites provide potential for some increase in a heat generation. There is an enormous potential within the Košice Basin, limited in an interest because of high salinity and scaling potential. By thermodynamic quality, a perspective in geothermal power production restricts to, if any, low-duty binary production only, which is, often, a most challenging problem in socioeconomic issues.

The paper briefly reviews distribution of key thermodynamic parameters of geothermal resources in the Western Carpathians and gives a first approach in analysis of its controls. Authors do believe, that presented thermodynamic database supporting previous characteristics will come profitable in a future R&D in geothermal energy in Slovakia.

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APPENDIX A: THERMODYNAMIC DATABASE - WELLS

Perspective geothermal area	T_{wh}		h_{field} (total)		h_{field} (normalized)		SExI (> 1500 m)		SExI (< 1500 m)	
	°C	class	kJ.kg^{-1}	class	–	class	–	class	–	class
Beša - Čičarovce structure	n/a	low	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Danube Basin Central Depression	28-91	low	398	low	402	low	0.044-0.045	low	0.049-0.07	moderate
Central Slovakian Neogene volcanites - NE	29-57	low	248	low	323	low	0.022-0.033	low	0.033	low
Central Slovakian Neogene volcanites – W,S	25-46	low	157	low	n/a	n/a	0.02	low	n/a	n/a
Dubník Depression	50-75	low	314	low	327	low	0.032	low	0.034	low
Upper Nitra Basin	20-59	low	339	low	446	low	0.048	low	0.07	moderate
Horné Strháre - Trenč Graben	39-35	low	123	low	346	low	0.025	low	n/a	n/a
Humenné Ridge	29-34	low	133	low	n/a	n/a	0.06	low	n/a	n/a
Ilava Basin	22-24	very low	118	low	n/a	n/a	0.005	low	n/a	n/a
Komárno High Block	20-30	very low	253	low	137	low	0.05	low	n/a	n/a
Komárno Marginal Block	42-64	low	241	low	323	low	0.018	low	0.018	low
Komjatice Depression	70-80	low	357	low	n/a	n/a	n/a	n/a	0.039	low
Košice Basin	123-129	moderate	610	moderate	620	moderate	n/a	n/a	0.102	moderate
Levice Block	69-80	low	349	low	350	low	0.037	low	0.04	low
Levoča Basin - NE	31-85	low	356	low	356	low	n/a	n/a	0.039	low
Levoča Basin - W,S	31-62	low	306	low	307	low	0.028	low	0.032	low
Liptov Basin	25-66	low	316	low	326	low	0.024-0.032	low	0.024	low
Lučenec - Rapovce Basin	35-40	low	168	low	168	low	0.009	low	n/a	n/a
Piešťany embayment	20-50	low	190	low	190	low	0.004	low	n/a	n/a
Rimava Basin	20-33	low	120	low	189	low	0.008-0.01	low	n/a	n/a
Skorušiná Basin	28-56	low	392	low	433	low	0.04-0.046	low	n/a	n/a
Topoľčany - Bánovce embayment	20-55	low	259	low	308	low	0.023-0.025	low	0.025-0.028	low
Trenčín Basin	n/a	low	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Trnava embayment	22-24	very low	121	low	121	low	0.05	low	n/a	n/a
Turiec Basin	50-60	low	320	low	320	low	0.029	low	n/a	n/a
Vienna Basin	73-78	low	390	low	390	low	n/a	n/a	0.045	low
Žilina Basin	24-41	low	281	low	305	low	0.019	low	0.038	low

APPENDIX B: THERMODYNAMIC DATABASE – PERSPECTIVE AREAS

Well, locality	b_{perf} (m)	T_{wh} (°C)	Reservoir stratigraphy -	h_{wh} $kJ.kg^{-1}$	s_{wh} $kJ.kg^{-1}.K^{-1}$	e_{wh} $kJ.kg^{-1}$	Ex MW	SExI (SExI)	η_{th} -	ε_{ut} -	SI -	IP -
Danube Basin Central Depression												
Čilistov, FGČ-1	1,549.00	52.00	Neogene	248.91	0.83	15.90	1.65	0.02	0.97	0.76	4.20	0.09
Čiližská Radvaň, ČR-1	2,430.00	82.00	Neogene	798.57	2.38	125.18	1.20	0.12	0.38	0.64	2.75	0.16
Čiližská Radvaň, VČR-16	1,745.00	64.00	Neogene	721.95	2.23	91.88	1.07	0.10				
Diakovce, Di-1	810.00	38.00	Neogene	382.36	1.26	25.53	0.05	0.03	0.85	0.67	3.03	0.01
Diakovce, Di-2	1,536.00	68.00	Neogene	487.89	1.53	56.48	1.42	0.06	0.79	0.64	2.80	0.18
Diakovce, Di-3	275.00	19.00	Neogene	146.51	0.51	2.64	0.02	*0.01*	1.00	0.39	1.64	0.01
Dunajská Streda, DS-1	2,432.00	91.00	Neogene	525.39	1.60	73.02	7.66	0.07	0.61	0.57	2.30	1.45
Dunajská Streda, DS-2	1,549.00	55.00	Neogene	384.88	1.24	34.76	1.28	0.04	0.83	0.65	2.89	0.15
Dunajský Klátov, VDK-15	2,222.00	74.00	Neogene	534.72	1.65	67.86	2.51	0.07				
Dvory nad Žitavou, FGDŽ-1	1,607.00	62.00	Neogene	357.61	1.15	33.06	0.81	0.04				
Gabčíkovo, FGGa-1	1,926.00	52.00	Neogene	414.63	1.34	37.33	0.41	0.04				
Galanta, FGG-1	1,670.00	62.00	Neogene	363.76	1.17	34.00	1.17	0.04	1.00	0.53	2.13	0.26
Galanta, FGG-2	2,032.00	80.00	Neogene	472.68	1.47	58.51	7.17	0.06	0.85	0.69	3.24	0.68
Galanta, FGG-3	1,999.00	77.00	Neogene	424.57	1.33	48.31	7.13	0.05	0.24	0.61	2.56	1.09
Horná Potôň, FGHP-1	1,804.00	68.00	Neogene	375.23	1.20	37.31	3.51	0.04				
Horná Potôň, VHP-12-R*	1,832.00	68.00	Neogene	383.70	1.22	38.76	3.72	0.04				
Chorvátsky Grob, FGB-1	1,150.00	47.00	Neogene	287.39	0.95	19.78	0.07	0.02				
Chorvátsky Grob, FGB-1/A	299.00	24.00	Neogene	207.19	0.71	6.43	0.01	0.01				
Kráľová pri Senci, FGS-1	570.00	23.00	Neogene	110.41	0.39	1.82	0.00	0.00				
Kráľová pri Senci, FGS-1/A	1,370.00	52.00	Neogene	245.65	0.82	15.49	1.55	0.02				
Lehnice, BL-1	1,455.00	54.00	Neogene	333.61	1.08	27.43	1.40	0.03				
Ňárad (Topoľovec) VTP-11	2,482.00	74.00	Neogene	760.17	2.30	109.43	1.92	0.11				
Nesvady, GN-1	1,494.00	60.00	Neogene	356.92	1.15	32.42	0.25	0.04	1.00	0.94	16.51	0.00
Nové Zámky, GNZ-1	1,473.00	59.00	Neogene	338.80	1.10	29.48	0.42	0.03	0.08	0.85	6.50	0.01
Poľný Kesov, BPK-1	737.00	26.00	Neogene	163.07	0.56	4.71	0.01	0.01				
Poľný Kesov, BPK-2	1,189.00	49.00	Neogene	310.08	1.02	23.02	0.17	0.03				
Rusovce, HGB-1	1,493.00	28.00	Neogene	120.88	0.42	2.51	0.00	0.00				
Senec, BS-1	1,181.00	49.00	Neogene	280.65	0.93	19.45	0.58	0.02	0.61	0.40	16.51	0.00
Sereď, SEG-1	1,800.00	66.00	Neogene	353.26	1.13	33.24	1.36	0.04	0.99	0.86	6.50	0.01

Well, locality	b_{perf} (m)	T_{wh} (°C)	Reservoir stratigraphy -	h_{wh} $kJ.kg^{-1}$	s_{wh} $kJ.kg^{-1}.K^{-1}$	e_{wh} $kJ.kg^{-1}$	Ex MW	SExI (SExI)	η_{th} -	ε_{ut} -	SI -	IP -
Danube Basin Central Depression												
Šaľa, GTŠ-1	1,786	69	Neogene	379.3	1.21	38.25	2.81	0.042	1.00	0.87	7.51	0.050
Šaľa, HTŠ-2	1,169	42	Neogene	266.4	0.89	16.23	0.08	0.020				
Šaľa, HTŠ-3	282	18	Neogene	151.2	0.53	2.54	0.01	0.006				
Šurany, GŠM-1	1,500	49	Neogene	268.0	0.89	17.91	0.19	0.022	0.42	0.22	1.29	0.113
Topoľníky, FGT-1	2,487	74	Neogene	555.2	1.71	71.62	3.62	0.074	0.95	0.83	5.97	0.102
Tvrdošovce, FGTv-1	1,637	70	Neogene	477.8	1.49	55.68	2.78	0.059	0.58	0.43	1.74	0.918
Veľký Meder (Čalovo), Č-1	1,791	79	Neogene	924.1	2.75	146.63	1.61	0.145	0.86	0.73	3.69	0.118
Veľký Meder (Čalovo), Č-2	1,439	57	Neogene	538.8	1.70	57.46	0.94	0.062	0.74	0.60	2.50	0.150
Vlčany, FGV-1	1,852	68	Neogene	487.9	1.53	56.48	1.19	0.060	0.57	0.42	1.72	0.402
Zemianska Oľča, VZO-14	1,839	74	Neogene	509.7	1.58	63.23	1.71	0.066				
Zlaté Klasy – Eliášovce, VZK-10	1,457	65	Neogene	317.4	1.03	27.18	2.82	0.031				
Zlatná na Ostrove, VZO-13	1,625	51	Neogene	241.0	0.80	14.81	0.83	0.019	0.75	0.58	2.36	0.149
Central Slovakian Neogene volcanites – SE part												
Banská Štiavnica, HR-1	829	46	Neogene	261.0	0.87	16.56	0.50	0.021				
Kalinčiakovo, HBV-1	70	25	Triassic	161.1	0.56	4.44	0.11	0.008	0.86	0.31	1.46	0.052
Kalinčiakovo, HBV-2a	49	25	Triassic	161.1	0.56	4.44	0.05	0.008				
Santovka, B-3A	64	26	Neogene	119.4	0.42	2.38	0.21	0.005	0.83	0.31	1.44	0.101
Central Slovakian Neogene volcanites – NW part												
Kremnica, KŠ-1****	531	47	Triassic	311.6	1.02	22.57	0.79	0.027	0.75	0.30	1.44	0.380
Lukavica, LKC-4	851	35	Triassic	386.4	1.28	23.81	0.10	0.030				
Sielnica, KMV-1	407	33	Triassic	177.5	0.61	6.66	0.04	0.010	1.00	0.69	3.18	0.004
Sklené Teplice, ST-4	1,695	57	Triassic	342.4	1.11	29.50	1.23	0.033	0.80	0.67	3.06	0.131
Sklené Teplice, ST-5	1,001	46	Triassic	253.4	0.84	15.69	0.19	0.020				
Topoľčianky, KD-1	500	27	Triassic	127.1	0.44	2.84	0.04	0.005				
Vyhne, H-1	78	36	Triassic	242.5	0.82	12.42	0.07	0.017	0.66	0.44	1.79	0.021
Vyhne, HGV-3	54	29	Triassic	199.3	0.68	7.45	0.04	0.011				
Zlatno, R-3	710	35	Neogene	165.7	0.57	5.91	0.30	0.009				

Well, locality	b_{perf} (m)	T_{wh} (°C)	Reservoir stratigraphy -	h_{wh} $kJ.kg^{-1}$	s_{wh} $kJ.kg^{-1}.K^{-1}$	e_{wh} $kJ.kg^{-1}$	Ex MW	SExI -	η_{th} -	ε_{ut} -	SI -	IP -
Dubník Depression												
Bruty, VTB-1	1,905	75	Neogene	332.19	1.07	30.57	13.76	0.034				
Svätý Peter, PTG-11	1,321	50	Neogene	246.51	0.82	15.41	0.49	0.019				
Želiezovce, HGŽ-1	234	18	Neogene	99.14	0.35	1.11	0.02	0.003				
Želiezovce, HGŽ-3	900	52	Neogene	239.17	0.80	14.65	0.22	0.018	0.68	0.79	4.82	0.009
Horné Strháre – Trenč Graben												
Dolná Strehová, HGDS-1	615	29	Neogene	296.64	1.00	13.56	0.01	0.019	1	0.70	3.34	0.001
Dolná Strehová, M-4	520	35	Neogene	386.37	1.28	23.81	0.02	0.030				
Slovenské Kľačany, TSK-1	600	38	Neogene	318.56	1.06	19.77	0.03	0.025				
Vinica, HG-18	320	21	Neogene	102.57	0.36	1.42	0.04	0.004	1	0.39	1.64	0.016
Upper Nitra Basin												
Handlová, FGHn-1	430	19	Palaeogene	179.92	0.63	3.67	0.00	0.008				
Handlová, RH-1	1,179	37.5	Palaeozoic	259.70	0.87	14.34	0.23	0.019				
Chalmová, BCH-3	120	39	Triassic	225.00	0.76	11.55	0.11	0.015	1.00	0.54	2.17	0.023
Chalmová, HCH-1	194	33	Triassic	204.75	0.70	8.70	0.15	0.012	0.40	0.55	2.24	0.030
Koš (Laskár), Š-1-NB II	1,851	59	Triassic	615.10	1.93	70.23	1.24	0.074	0.47	0.37	1.59	0.488
Humenné Ridge												
Kaluža, GTH-1	594	34	Triassic	163.07	0.56	5.64	0.05	0.009				
Sobrance, TMS-1	625	29	Neogene	127.37	0.44	2.92	0.14	0.006	0.92	0.56	2.30	0.026
Komárno High Block												
Kravany, FGKr-1	1,021	20	Triassic	136.97	0.48	2.53	0.01	0.005				
Obid, FGO-1	1,000	20	Triassic	136.97	0.48	2.53	0.00	0.005	1.00	0.43	1.75	0.001
Patince, SB-1	160	26	Triassic	194.00	0.67	6.37	0.13	0.010				
Patince, SB-2	146	27	Triassic	202.96	0.69	7.14	0.22	0.011				
Patince, SB-3	167	26	Triassic	194.00	0.67	6.37	0.13	0.010	1.00	0.05	1.05	0.119
Štúrovo, FGŠ-1	210	40	Triassic	321.53	1.06	20.96	1.17	0.026	0.72	0.53	2.11	0.262
Štúrovo, VŠ-1	125	39	Triassic	330.88	1.10	21.39	0.73	0.026				
Virt, vrt JRD	260	26	Triassic	194.00	0.67	6.37	0.03	0.010				
Virt, HVB-1	241	26	Triassic	194.00	0.67	6.37	0.04	0.010	0.72	0.43	1.75	0.015
Virt, vrt VŠE	280	24	Triassic	176.73	0.61	4.99	0.06	0.009	0.99	0.58	2.36	0.011

Well, locality	b_{perf} (m)	T_{wh} (°C)	Reservoir stratigraphy -	h_{wh} $kJ.kg^{-1}$	s_{wh} $kJ.kg^{-1}.K^{-1}$	e_{wh} $kJ.kg^{-1}$	Ex MW	SExI -	η_{th} -	ε_{ut} -	SI -	IP -
Komárno Marginal Block												
Komárno, FGK-1	1,964	64	Triassic	392.91	1.25	39.19	0.38	0.043				
Komárno, M-1	1,221	42	Triassic	237.55	0.79	13.30	0.05	0.017				
Komárno, M-2	1,025	42	Neogene	210.61	0.71	10.56	0.19	0.014				
Komárno, M-3	1,184	51	Triassic	280.18	0.92	19.77	0.31	0.024				
Marcelová, GTM-1	1,761	56	Neogene	237.05	0.79	14.49	7.83	0.018				
Komjatice Depression												
Komjatice, G 1	1,700	78	Neogene	357.29	1.1391	35.513	8.5658	0.0387				
Košice Basin												
Ďurkov, GTD-1	3,155	125	Triassic	616.89	1.81	104.52	175.60	0.102				
Ďurkov, GTD-2***	3,104	129	Triassic	644.49	1.88	113.32	169.99	0.110				
Ďurkov, GTD-3***	2,246	123	Triassic	600.54	1.77	99.53	200.55	0.098				
Košice, G-4	273	26	Triassic	122.18	0.43	2.53	0.06	0.005	1	0.53	2.13	0.012
Šebastovce, KAH-6	149	18	Neogene	86.01	0.30	0.75	0.03	0.003				
Valaliky, KAH-3	171	21	Neogene	108.50	0.38	1.63	0.03	0.004				
Valaliky, KAH-5	148	21	Neogene	152.33	0.53	3.28	0.03	0.007				
Levice Block												
Podhájska, GRP-1*	1,365	69	Triassic	311.60	1.01	26.58	14.29	0.030				
Podhájska, Po-1	1,740	80	Neogene	368.91	1.17	37.93	39.40	0.041	0.71	0.46	1.86	11.344
Levoča Basin – NE part												
Lipany, L-1*****	3,390	85	Triassic	441.62	1.37	53.44	5.02	0.056				
Plavnica, Pl-1	3,360	65	Palaeogene	309.60	1.00	25.93	1.30	0.030				
Plavnica, Pl-2	3,010	53	Palaeogene	240.10	0.80	4.82	0.73	0.018				
Levoča Basin - S, W part												
Arnutovce, HKJ-3	1,133	31	Triassic	185.50	0.63	6.95	0.11	0.010				
Letanovce, HKJ-4	589	25	Triassic	198.68	0.68	6.33	0.03	0.010				
Poprad, PP-1	1,128	48	Triassic	265.32	0.88	17.42	2.99	0.021	1.00	0.80	5.05	0.117
Stará Lesná, FGP-1	2,092	58	Triassic	330.76	1.07	28.07	1.98	0.032				
Veľká Lomnica, GVL-1	2,100	62	Triassic	354.80	1.14	32.63	4.00	0.036				

Well, locality	**b_{perf} (m)**	**T_{wh} (°C)**	**Reservoir stratigraphy -**	**h_{wh} $kJ.kg^{-1}$**	**s_{wh} $kJ.kg^{-1}.K^{-1}$**	**e_{wh} $kJ.kg^{-1}$**	**Ex MW**	**SExI (SExI)**	**η_{th} -**	**ε_{ut} -**	**SI -**	**IP -**
Levoča Basin – S, W part												
Veľký Slavkov, VSČ-1	2,353	57	Triassic	315.61	1.03	25.69	2.43	0.030	0.14	0.84	6.12	0.065
Vrbov, Vr-1	1,734	56	Triassic	298.90	0.98	23.13	2.62	0.027	0.64	0.62	2.61	0.384
Vrbov, Vr-2	1,983	59	Triassic	320.38	1.04	26.78	3.53	0.031	0.83	0.84	6.29	0.089
Liptov Basin												
Bešeňová, FBe-1	400	25	Triassic	120.42	0.42	2.39	0.05	0.005	1.00	0.51	2.06	0.011
Bešeňová, FGTB-1	1,814	66	Triassic	407.40	1.29	42.16	4.05	0.046	0.60	0.61	2.57	0.613
Bešeňová, ZGL-1	1,987	62	Triassic	370.73	1.19	35.08	2.84	0.039				
Liptovská Kokava, ZGL-3	2,365	43	Triassic	212.36	0.71	10.85	0.95	0.014				
Liptovský Trnovec, ZGL-2/A	2,486	60	Triassic	316.30	1.03	26.32	3.83	0.030	0.81	0.49	1.96	0.996
Pavčina Lehota, FGL-1	1,570	32	Triassic	298.28	1.00	15.24	0.05	0.021				
Lúčenec Basin/Rapovce structure												
Rapovce, GTL-2	1,439	38	Triassic	167.92	0.57	6.23	0.88	0.009				
Ilava Basin												
Belušské Slatiny, BHS-3	30	22	Triassic	118.55	0.41	2.11	0.02	0.005	1.00	0.46	1.86	0.007
Piešťany embayment												
N. Mesto n. V.-Zel. Voda, GZV-1	1,155	19.4	Triassic	110.46	0.39	1.57	0.02	0.004				
Rimava Basin												
Cakov, BČ-3	874	29	Triassic	133.36	0.46	3.30	0.06	0.006				
Rimavské Janovce, GRS-1	1,008	33	Triassic	189.09	0.64	7.53	0.17	0.011				
Tornaľa, HM-5	158	18	Triassic	96.52	0.34	1.04	0.08	0.003	1.00	0.27	1.37	0.045
Skorušiná Basin												
Oravice, OZ-1	561	28	Triassic	200.29	0.68	7.25	0.20	0.011				
Oravice, OZ-2	1,565	56	Triassic	433.34	1.39	41.94	5.45	0.046	0.03	0.57	2.34	0.992
Topoľčany – Bánovce embayment												
Bánovce n/ Beb., BnB-1	2,025	40	Triassic	343.54	1.13	23.06	0.27	0.028	0.76	0.57	2.32	0.051
Brodzany, HGT-9	139	32	Triassic	188.77	0.64	7.35	0.02	0.011				
Malé Bielice, MB–3	100	40	Palaeogene	279.49	0.93	16.94	0.16	0.021	0.72	0.51	2.04	0.038
Partizánske, FGTz-2	970	33	Triassic	261.81	0.88	12.99	0.11	0.018	0.41	0.73	3.74	0.008
Partizánske, HGTP-1	474	20	Triassic	144.56	0.50	2.79	0.04	0.006				

Well, locality	**b_{perf} (m)**	**T_{wh} (°C)**	**Reservoir stratigraphy -**	**h_{wh} $kJ.kg^{-1}$**	**s_{wh} $kJ.kg^{-1}.K^{-1}$**	**e_{wh} $kJ.kg^{-1}$**	**Ex MW**	**SExI (SExI)**	**η_{th} -**	**ε_{ut} -**	**SI -**	**IP -**
Topoľčany – Bánovce embayment												
Topoľčany, FGTz-1	1,917	55	Triassic	272.01	0.90	19.28	0.23	0.023	0.55	0.31	1.45	0.108
Veľké Bielice, VB-3	90	39	Palaeogene	309.92	1.03	19.43	0.13	0.024	0.60	0.62	2.66	0.018
Trnava embayment												
Koplotovce, KB-1	108	24	Triassic	121.74	0.42	2.39	0.09	0.005				
Turiec Basin												
Turčianske Teplice, TTŠ-1	1,124	54	Triassic	320.67	1.04	25.71	0.80	0.030	0.93	0.74	3.85	0.054
Vienna Basin												
Lakšárska Nová Ves, RGL-1	2,065	78	Neogene	418.55	1.31	47.36	8.05	0.050				
Šaštín-Stráže, RGL-2	2,570	73	Neogene	352.87	1.13	34.21	4.47	0.038				
Žilina Basin												
Kamenná Poruba, RTŠ-1	1,814	41	Triassic	430.56	1.41	32.16	0.22	0.038				
Rajec, RK-22	1,308	26	Triassic	228.02	0.78	8.19	0.09	0.013	0.93	0.21	1.26	0.057
Stráňavy, ŽK-2	550	24	Palaeogene	233.84	0.80	7.68	0.07	0.013	0.65	0.38	1.62	0.026

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5. Hydrogeochemistry of Surface Water in Slovakia

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Abstract: The paper provides information on characteristics and genesis of surface water in Slovakia. The focus is in the chemical and isotopic analyses of samples of surface water. The input data are represented by 10,960 samples within the geochemical mapping of Slovakia. The interpretation is based on a conceptual model of the formation of the chemical composition of the surface water in the conditions of the Western Carpathians. Based on its end members formation, the surface water is divided on the basis of five dominant types of lithogeochemical environs in watersheds. Individual earmarked end types are characterized on the basis of statistical methods and thermodynamic modelling. According to composition of oxygen and deuterium isotopes the molecule of water itself is clearly of meteoric origin. Approximately 6.5% of the main ions content is of the same origin. The rest of the chemical composition of a surface stream is caused by the interaction of water – rock – gas. Its source is the direct interaction in the bed, and wash-off and inflow of groundwater into a surface stream. The last factor of the chemical composition formation are anthropogenic impacts of different nature.

Key words: surface water, atmospheric deposition, stream water chemistry, anthropogenic impacts, stream water isotope composition, thermodynamic modelling

5.1 Introduction

Hydrogeochemical research focused on natural waters has a long tradition in Slovakia. It is focused in absolute majority on assessment of groundwater (fresh, mineral and geothermal), its chemical and isotopic composition, genesis, anthropogenic influence, protection, etc.

In the scope of the project of geochemical mapping of Slovakia there was obtained a large amount of initial information on the distribution of elements in groundwater, rocks, soils, river sediments, natural radioactivity and forest biomass. These data were published in the edition of Geochemical atlases of Slovakia at scale 1:1,000,000 (Rapant et al., 1996, Marsina et al., 1999, Čurlík and Šefčík, 1999, Bodiš et al., 1999, Daniel et al., 1996, Maňkovská, 1996). The latest edition of this series was the Geochemical Atlas of the Slovak Republic – Surface Water (Bodiš et al., 2015). Chemical analyses of the Atlas have given a momentum to hydrogeochemical assessment of surface water in Slovakia.

The surface water plays an important role in the hydrological cycle. The genesis and the chemical composition of surface water have been studied already for many decades in order to obtain knowledge of the distribution of components and elements in the water, their mobility and the processes influencing them. In addition, there was also an effort to learn the processes, extent and rate of chemical and physical weathering and transport of continental weathering products into the world ocean. These studies provide important information on the consumption of CO_2 at the acidic degradation of continental rocks (e.g. Stallard & Edmond, 1983; Meybeck, 1987; Probst et al., 1992; Gaillardet et al., 1997; Roy et al., 1999; Picouet et al., 2002). In terms of hydrogeochemistry there is important to learn also the quality of surface water flows due to the possibility of its use as a source of water for drinking, irrigation, industrial use, etc.

Globally, we can say that in the process of the Earth's hydrological cycle, the chemical composition of the water is formed in the environment interconnecting the hydrosphere with the atmosphere, lithosphere and biosphere. As a result of interaction of all these components with the nature of the country and anthropogeneous activities, the water contains a wide range of various components, gasses, colloids, etc. Regarding the physical-chemical water properties the above stated interactions are conditioning the large variability of the water chemical composition.

Already in the 20th century, the scientists have tried to compile models of the key processes, forming the chemical composition of the surface water (rivers and lakes). The geochemical model, being one of the earliest and also the most criticized, is so-called boomerang model (Gibbs, 1970).

The boomerang shape of the Gibbs' model is formed by the graphic representation of cations and anions in $mg \cdot l^{-1}$. At cations it was a ratio Na/(Na + Ca) to the TDS and at anions $Cl/(Cl + HCO_3)$ to the TDS of the water. The resulting model has provided a ground for a hypothesis, which reflected the relative significance of three fundamental mechanisms controlling the chemical composition of the world's surface water.

The bivariate model assumes, that water with low TDS and high content of sodium and chlorides has a chemical composition with the dominant representation of atmospheric precipitation. The water with a medium value of TDS and high calcium and bicarbonate content originates by the water-rock interaction and the water with a high value of TDS and high contents of sodium and chlorides originates by evaporation.

The Gibbs' model was controversial. It distinguished only three factors of formation of the chemical composition of surface water. Feth (1971) responded by opinion that bivariate model does not distinguish between input sources with salt water and evaporation. Similarly according to Stallard & Edmond (1983), the water from the Amazon River has a high value of TDS and high sodium content. Their origin is attributed preferably to the dissolution of evaporites than the evaporation process. These authors also identified other water formations, which chemical composition of the water was a result of weathering of silicate rocks, while the bivariate model assumes that their composition is a product of atmospheric precipitation. The data by Kilham (1990) of the rivers and lakes in Africa, which due to geological environment were alkaline and salt, have indicated a significant divergence from the boomerang shape of the Gibbs' model. It was just a modification of the model, resp. its shape.

Numerous authors (Eilers et al., 1992; Armengol et al., 1991; Gibson et al., 1995; Baca & Threlkeld, 2000, etc.) suppose that Gibbs' model is not an appropriate model for the expression of the key processes, controlling the chemical composition of the world's surface streams and lakes. For these reasons, this bivariate model is currently used as a null model for comparing the regional chemical composition of the surface water.

The problem is mainly that the model does not consider the other ions, which play an important role in identifying the geochemical processes forming the surface water, especially in complicated geological conditions, such as those in the Western Carpathians. Another disadvantage represents the distance of the drainage basin of the surface flow from the ocean.

The ternary diagrams that take into account a combination of several cations and anions of chemical composition of the surface water seem to be more suitable. Chemical composition of the surface water is often subject to multivariate statistical analysis as e.g. cluster analysis, the method of principal components or factor analysis. These analyses also allow to find hidden relationships between the analysed ions as well as the trace elements. At the trace elements, however, there is a problem at a high representation of values below a limit of determination. Just datasets of trace elements in the surface water are characteristic in many cases with very low concentration. The advantage of the statistical processing is that it allows evaluation of the complex data as e.g. inorganic and organic substances, flow volume, water temperature, etc., altogether in one file (e.g. Shrestha & Kazama, 2007).

According to Garrels & MacKenzie (1971), in the global concept the dissolved solids in water surface flows originate from different sources, such as rainwater and weathering of siliceous, carboniferous and evaporitic rocks. It can be said that in the vast majority of large rivers the direct access of precipitation is less significant (less than 5%), except for the flows influenced by evaporation (Gaillardet et al., 1999).

Generally the hydrogeochemical models of chemical composition of the surface flows are based on analysis of the end members, the composition of which is derived from the data from small basins with homogeneous geological environment (silicates, carbonates, evaporites, etc.). The resulting chemical composition of surface water is assessed by mixing of these end members. Often, there is used a combination of Sr isotope and the molar ratios Ca/Sr, Mg/Na and Ca/Na or HCO_3/Na and Ca/Na (e.g. Négrel et al., 1993).

For various reasons, many authors tried to estimate the average chemical composition of the world's surface waters. It was mostly a compilation of chemical composition of large rivers. Obviously, the chemical composition of the surface water of the Earth is very variable. The high variability is due to many reasons. On the one hand they are represented by climatic conditions, distance from the ocean, the composition of the geological environment, topography, etc. This shows that a mean value represents mainly the first comparison with the data from a particular river basin. On the other hand, this variability is caused by the time factor and seasonality, and differing from the average ocean water; it is not possible to suppose its stability.

Often referred to average chemical composition of the surface water according to Livingstone (1963) is presented in Table 5.1. Meybeck (1979) has compiled newer data about the surface waters in the world (Table 5.1). These average values of the total concentration are lower, as the values published by Livingstone (1963). Both averages are strongly influenced by the chemical composition of large rivers. For comparison, the Table 5.1 presents the chemical composition of the largest river, the Amazon, from a single sample taken before reaching its delta in the Obidos (Oltman, 1968). When compared to the average chemical composition of the world's rivers, Amazon has a lower content of all ions. This is more or less due to the time of sampling, when its flow rate was maximum and reached 216,000 $m^3.s^{-1}$. An important factor is also an inactive rock environment of the river basin and low population. Oltman (1968) has estimated the average annual flow rate of the Amazon River at the mouth to Atlantic Ocean 175,000 $m^3.s^{-1}$.

Tab. 5.1 The average chemical composition of surface waters in the world.

Component	1	2	3	4
SiO_2	13.1	10.4	13.5	7
Ca	15	13.4	35.9	4.3
Mg	4.1	3.35	8.7	1.1
Na	6.3	5.15	4	1.8
K	2.3	1.3	1.3	
HCO_3	58.4	52	123.1	19
SO_4	11.2	8.25	25.8	3
Cl	7.8	5.75	2.4	1.9
TDS	118.2	89.2	208.9	38.1

Note: 1 – according to Livingstone (1963); 2 – according to Meybeck (1979); 3 – Slovakia after Bodiš et al. (2015); 4 – composition of the Amazon River at the locality Obidos (Brazil) according to Oltman (1968); values are in $mg{\cdot}l^{-1}$.

The Table 5.1 presents also the average composition of the surface water in Slovakia (column 3). The values are calculated from the 7,862 samples of chemical analyses of the surface water, which relevant part of the basin consists of homogeneous rock environment and there is an assumption of minimum anthropogenic impact. They represent so-called clean water or end members of the streams.

Compared to the average chemical composition of the global surface water according to Livingstone (1963), resp. Meybeck (1979), the Slovak surface waters have higher value of the total dissolved solids. From individual ions they most distinctly differ by the concentration of bicarbonates, calcium, magnesium and sulphate, which have higher average values. On the other side, there is interesting that average contents of SiO_2 and potassium are nearly similar and concentration of sodium and chlorides is in Slovak surface water lower. However, such comparisons are only indicative, because of strong influence by numerous factors.

5.2 Share of Slovakia on the global and European water cycle

The estimate of the total amount of the water in the hydrosphere is necessary for understanding the role of water in the Earth system, as well as for providing the base data for rational water management fulfilling the needs of a man and environmental protection. Recently existing several global estimates mutually differ to some extent. Based on the UNESCO (1978) data, the total evaporation from the seas ($505 \cdot 10^3$ km^3) returns to continents $50 \cdot 10^3$ km^3 of the water. The rest of the water returns back into the sea by rainfalls. The total amount of precipitation fallen on the continents is around $110 \cdot 10^3$ km^3, but app. $45 \cdot 10^3$ km^3 returns back to see by the water flows.

Leaving the global balance estimates, the European continent registers an average rainfall 657 mm. From this amount, 306 mm flow away and the rest 351 mm evaporates. Area of Slovakia represents only three hundredths percent of the world mainland and less than half percent of total European area (0.47%). The outflow from Slovakia participates in the mainland runoff amount less than by three hundredths percent (0.027%) and within European continent the outflow represents 0.4%. Specific runoff in Slovakia, compared with the mainland value (10.0 $l \cdot s^{-1} \cdot km^{-2}$) and the value from the whole European continent (9.7 $l \cdot s^{-1} \cdot km^{-2}$) is lower and reaches only 8.26 $l \cdot s^{-1} \cdot km^{-2}$. This is caused by relatively large lowland areas with lower amount of water in the southern Slovakia. The catchment areas where the total available water sources in Slovakia have been formed, represent 0.16% of the mainland and 2.28 % of the area of European continent. The runoff from this area is represented with approximately the same percentage. In the first case it is up to 0.2% and in the second case 2.9%. Disproportional higher is the specific runoff from this territory (12.5 $l \cdot s^{-1} \cdot km^{-2}$), mainly due to a high specific runoff of the Danube River.

The existence of water sources and population density in certain area represent principal determinants of its development. The population growth and increasing demands on the standards of living, the pollution of water sources and devastation of the natural environment generally cause the decrease of the ratio of usable water sources per inhabitant. According to WMO data (Shiklomanov, 1991), this ratio lowers in the Europe from $5.9 \cdot 10^3$ m^3 in 1950 to $4.6 \cdot 10^3$ m^3 in 1980. In Central Europe it is the decrease from $3.0 \cdot 10^3$ m^3 to $2.4 \cdot 10^3$ m^3 for inhabitant per year. For illustration there is perhaps worth to state known extreme values: e.g. in Canada it is $384 \cdot 10^3$ m^3 and $219 \cdot 10^3$ m^3 and in the northern Africa $2.3 \cdot 10^3$ m^3 and $0.69 \cdot 10^3$ m^3. These values simultaneously document also irregular macrospatial distribution of water sources on the mainland.

In this spatial division there is interesting a position of Slovakia. If we take into account only sources generated in the Slovak territory, then dated to 1990 it is $2.4 \cdot 10^3$ m^3 for one inhabitant per year. It corresponds with value in the Central Europe region. If we take into consideration also the water sources formed outside Slovakia, which are inflowing to our territory, or they touch it along borders, then this ratio represents $17.74 \cdot 10^3$ m^3 for an inhabitant per year. The data represent estimates as the long-term averages, greater or lesser temporal variability.

5.3 Material and methods

Input for hydrogeochemical assessment of surface water database of Slovakia were 10,960 samples of Geochemical Atlas, part Surface Water (Bodiš et al., 2015). The Atlas compiling was based on the chemical analyses of surface water acquired by own collection of 2,400 samples, combined with chemical analyses obtained by archive retrievals. These contained 169 analyses from the Partial Monitoring System in the national monitoring network

Tab. 5.2 Summary of the determined indicators, limits of determination, analytical methods and applied equipments.

Indicator	Limit of determination	Unit	Analytical method	Equipment type
pH	1.0		E	electrochemical analyser EP-100, laboratory pH meter InoLab pH 730
conductivity μS·cm⁻¹	1	$\mu S \cdot cm^{-1}$	E	laboratory conductometer InoLab 730, conductometer Multi 340i
O_2	0.2	$mg \cdot l^{-1}$	E	oximeter InoLab 730 OXI
O_2	0.1	%	E	oximeter InoLab 730 OXI
Acidity ($ZNK_{8.3}$)	0.04	$mmol \cdot l^{-1}$	OA	
Alkalinity ($KNK_{4.3}$)	0.04	$mmol \cdot l^{-1}$	OA	
(Ca + Mg)	0.05	$mmol \cdot l^{-1}$	OA	
Total dissolved solids		$mg \cdot l^{-1}$	calculation	
COD_{Mn}	0.5	$mg \cdot l^{-1}$	OA	
Li	0.01	$mg \cdot l^{-1}$	AES-ICP	Varian – Vista MPX
Na	0.05	$mg \cdot l^{-1}$	AES-ICP	Varian – Vista MPX

Indicator	Limit of determination	Unit	Analytical method	Equipment type
K	0.1	$mg \cdot l^{-1}$	AES-ICP	Varian – Vista MPX
Ca	0.2	$mg \cdot l^{-1}$	AES-ICP	Varian – Vista MPX
Mg	0.2	$mg \cdot l^{-1}$	AES-ICP	Varian – Vista MPX
Sr	0.002	$mg \cdot l^{-1}$	AES-ICP	Varian – Vista MPX
Fe	0.007	$mg \cdot l^{-1}$	AES-ICP	Varian – Vista MPX
Mn	0.002	$mg \cdot l^{-1}$	AES-ICP	Varian – Vista MPX
NH_4	0.05	$mg \cdot l^{-1}$	F	spectrophotometer UV-VIS-DR 500
F	0.1	$mg \cdot l^{-1}$	IC	ion chromatograph Dionex DX-120, Dionex ICS 900
Cl	1	$mg \cdot l^{-1}$	IC	ion chromatograph Dionex DX-120, Dionex ICS 900
SO_4	2	$mg \cdot l^{-1}$	IC	ion chromatograph Dionex DX-120, Dionex ICS 900
NO_2	0.01	$mg \cdot l^{-1}$	F	spectrophotometer UV-VIS-DR 500
NO_3	1	$mg \cdot l^{-1}$	IC	ion chromatograph Dionex DX-120, Dionex ICS 900
PO_4	0.03	$mg \cdot l^{-1}$	F	spectrophotometer UV-VIS-DR 500
HCO_3	0.05	$mg \cdot l^{-1}$	OA	
CO_3	0.05	$mg \cdot l^{-1}$	OA	
OH	0.05	$mg \cdot l^{-1}$	OA	
SiO_2	0.2	$mg \cdot l^{-1}$	AES-ICP	Varian – Vista MPX
Free CO_2	0.05	$mg \cdot l^{-1}$	calculation	
Aggressive CO_2	1.1	$mg \cdot l^{-1}$	calculation	
Cr	0.002	$mg \cdot l^{-1}$	AES-ICP	Varian – Vista MPX
Cu	0.002	$mg \cdot l^{-1}$	AES-ICP	Varian – Vista MPX
Zn	0.002	$mg \cdot l^{-1}$	AES-ICP	Varian – Vista MPX
As	0.001	$mg \cdot l^{-1}$	AAS-GH	Atomic absorption spectrophotometer SPECTR AA 220
Cd	0.0003	$mg \cdot l^{-1}$	AES-ICP	Varian – Vista MPX
Se	0.001	$mg \cdot l^{-1}$	AAS-GH	Atomic absorption spectrophotometer SPECTR AA 220
Pb	0.005	$mg \cdot l^{-1}$	AES-ICP	Varian – Vista MPX
Hg	0.0001	$mg \cdot l^{-1}$	AAS	mercury analyzer AMA - 254
Ba	0.002	$mg \cdot l^{-1}$	AES-ICP	Varian – Vista MPX
Al	0.02	$mg \cdot l^{-1}$	AES-ICP	Varian – Vista MPX
Sb	0.001	$mg \cdot l^{-1}$	AAS-GH	Atomic absorption spectrophotometer SPECTR AA 220

Notes:

• AAS	• atomic absorption spectrometry
• AAS-GH	• atomic absorption spectrometry with hydrides generating
• AES-ICP	• atomic absorption spectrometry with inductively coupled plasma
• OA	• volumetric analysis
• E	• electrochemistry
• VTO	• high-temperature combustion with non-dispersive infrared detector
• ISE	• ion selective electrode
• ITP	• isotachophoresis
• IC	• ion chromatography
• F	• spectrophotometry

of surface water, 6,463 chemical analyses from the map sets of the geological factors of the environment, as well as 1,928 analyses from other works. The main requirement for the inclusion of the sample into the database was a complete chemical analysis of the main compounds. The analysis error must not exceed 5% and the sampling sites must have known coordinates. The total number of the samples in the database has reached the number of 10,960 chemical analyses. As for the laboratory work, approximately 80% of chemical analyses were done in the accredited Geoanalytical Laboratories of the State Geological Institute of Dionýz Štúr Spišská Nová Ves, operating as a reference laboratory for the water analyses in Slovakia.

A list of rated indicators with the Limits of determination, applied analytical method and equipment is presented in Table 5.2.

The quality control of analytical data was expressed in two levels: internal and external. The internal quality control was assured by analysis of reference material, repeated sample analysis of single and multiple sampling.

External quality control was ensured by participation in interlaboratory comparison tests.

The quality policy of the laboratory represents a systematic care about the services quality in securing, maintaining and improving quality in all activities, relating to the implementation of accredited tests.

The samples for the stable isotopes analyses were taken into the glass bottles with the double bell (medicine bottles) with a volume of 0.05 or 0.1 litre. The samples were collected as possible beneath the water surface from a depth of 10 – 30 cm, to prevent against possible sampling of evaporated water. Samples from the collection in August 2013 were transported to the Laboratory of Isotope Geology in SGIDŠ Bratislava. Each sample was filtered, and aliquot parts were poured into two sample bottles (glass bottles with a volume of 0.01 l with a double seal). One was postponed into the register and the second was used for isotopic analysis. The samples are stored in a refrigerator at ~ 4 °C.

New samples were analysed by the Liquid-Water Isotope Analyser (LWIA; *Los Gatos Research Inc.*), which uses a highly-resolved laser absorption spectroscopy for the simultaneous measurement of ratios of stable isotopes deuterium/hydrogen ($^2H/^1H$) and $^{18}O/^{16}O$ oxygen in the water samples. The laser beam passes through an evacuated cavity, into which an aqueous sample is injected. Laser Absorption Spectroscopy uses the Beer-Lambert Law, which relates the absorbance of laser radiation with the water vapour isotopic composition of the samples (Ricci, 1994). For the preparation of the measurement there is used 1 ml of the water dispensed in 1.5 ml vials with screw lids with a penetrable septum (PTFE/silicone/PTFE). To the analysis there is used about 600 to 850 μl of the sample in six injections and double repetition. Samples are analysed in a sequence with the three internal standards calibrated in comparison with the commercially available standards from the firm Iso-Analytical Limited (IA-R052 – $\delta^2H_{V\text{-}SMOW} = -157.12 \pm 1.35‰$, $\delta^{18}O_{V\text{-}SMOW} = -19.64 \pm 0.11‰$; IA-R053 – $\delta^2H_{V\text{-}SMOW} = -61.97 \pm 2.1‰$, $\delta^{18}O_{V\text{-}SMOW} = -10.18 \pm 0.20‰$;, IA-R054 – $\delta^2H_{V\text{-}SMOW} = 4.93 \pm 0.85‰$, $\delta^{18}O_{V\text{-}SMOW} = 0.56 \pm 0.23‰$). Set values are in an established δ-notation – $\delta\ (‰) = [(R_{sample}/R_{standard} - 1] \times 1{,}000$, where R represents a molar ratio of the heavier isotope in relation to easier isotope (e.g. $^{18}O/^{16}O$) in sample and standard. The standard inaccuracy at δ^2H is 2‰ and at $\delta^{18}O$ it is ± 0.2‰.

In a part about the isotopic composition of the surface water there is stated that the water molecule itself has clearly meteoric origin. In the formation of the chemical composition of the surface water, the initial water is represented by rainwater, but its share on the total dissolved solids content is only 6.5%. The conceptual model of end members of chemical composition of the surface water contains a lot of other factors, constituting a source of ions in the final composition of the surface water at a certain time and space. This are particularly the interactions of the rainwater with the vegetation cover, soil profile and the rock environment. Such model is considerably simplified, but sufficient for evaluating the results of the nationwide geochemical mapping in Slovakia at a scale 1:1,000,000.

Under the end members of the formation of chemical composition of the surface water we mean the water samples, bound to relevant catchments area, being built of homogeneous geological environment. At the same time, these samples do not show signs of anthropogenic influence.

The selection of the sample sets, which meet these criteria, took place in several steps. The first one was the upstream assigning of each water sample to the appropriate catchment area, which formed the anticipated space of its chemical composition formation. Given assignment was done by a macro application in the MapInfo Professional 10.0 software environment (Slaninka, 2006).

To generate a relevant part of the catchment area with a homogenous rock environment, after testing there suits best (in terms of the water-rock interaction) the division based on the rock types (lithotypes). This simplification is mainly based on petrographic and geochemical properties. Lithotypes do not take into account the age of rocks, only their composition, allowing by this way to characterize the geochemical processes (interactions) with this environment. There is also important that this categorization of the rock (geological) environment includes the age and genetically undivided rocks from Palaeozoic ones up to Quaternary sediments. Obviously, it is difficult or impossible to name allocated rock groups generally according to the area, tectonic unit, etc., because in terms of petrographic and geochemical characteristics in many cases they overlap.

In simple substantiation, the geological environment is divided into five groups, named A, B, C, D and E, which are characterized by petrography and geochemistry with examples of the main rock types representation. In Table 5.3 these five types have allocated all 54 pre-Quaternary and 3 Quaternary lithotypes sensu Marsina et al. (1999). Division into five groups:

A) Acid alumosilicate rocks and siliciclastic sediments, as well as their metamorphic rock equivalents (represented mainly by: granites and granitoids, rhyolites, eolian sands, gneisses, etc.)
B) Basic and intermediary rocks (represented mainly by andesites, diorites, intermediary and mafic volcanites, etc.)
C) Dominantly pelitic sediments (represented mainly by clays and claystones, loamy swamp sediments, etc.)
D) Dominantly siliciclastics rocks (represented mainly by sandstones, sandy shales, sandy and gravel sediments, etc.)
E) Carbonate rocks (represented mainly by limestones and dolomites, clay and sandy limestones, conglomerates, etc.)

Tab. 5.3 Selection of lithotypes.

	Geochemical type of rocks
	Quaternary
A	Eolian siliceous sands
C	Humic alluvial clay and argillaceous sediments
D	Sand, sandy gravel, loess
	Neogene
E	Freshwater limestone – travertine
C	Clays, sand, gravel, lignite interbeds
C	Clays, sands, and tuffite volcanomictic sediments, lignite interbeds
C	Calcareous claystones and siltstones
C	Calcareous clays, sandstone, gravel, limestone, lignite interbeds
C	Calcareous clays, sandstone, gravel, limestone, tuffite and volcanomict sediments
C	Calcareous clays, sandstone, gravel, limestone and gravel
	Neogene volcanites
B	Alkaline basalts
B	Basalts and basaltic andesites
B	Pyroxene and amphibole-pyroxene andesites
B	Pyroxene-amphibole, amphibole and biotite-amphibole andesites to dacites
B	Propylitized andesites, andesite porphyry, diorite, porphyry and diorite
A	Granodiorite, granodiorite porphyry, quartzy diorite, porphyries
A	Rhyodacites and rhyolites
	Inner Carpathian Palaeogene
C	Claystones, marlstones, sandstones, conglomerates, limestone and coal, Palaeogene of the Buda Development
D	Sandstones, sporadical clays, Biely Potok Formation
C	Calcareous claystones, sandstones, Huty and Zuberec formations
D	Sandstones, conglomerates, breccias, limestones, Borové Formation
	Cretaceous and Palaeogene of Outer Carpathians
D	Prevailing sandstones, sporadical claystones, flysch of the Magura Unit
D	Sandstones and claystones, flysch of Magura Unit
D	Predominant claystones, sporadic sandstones, flysch of the Magura Unit
D	Prevailing sandstones, sporadic claystones, flysch of the Dukla (Silesia) units
D	Sandstones and claystones, flysch of the Dukla (Silesia) units
D	Predominant claystones, sporadic sandstones, flysch of the Dukla Unit
	Clayey-sandy sediments of the Cretaceous and Palaeogene of Klippen Belt, Tatricum and Hronicum
C	Marls, carbonatic sandstones, conglomerates, limestones, prevailingly calcareous flysch
C	Variegated marlstones
	Mesozoic of the Klippen Belt and the Central Western Carpathians
E	Limestones
E	Limestones and dolomites
E	Dolomites
E	Limestones, dolomites and shales (phyllites)
E	Limestones, dolomites, shales (phyllites) and mafic volcanites
E	Prevailing clayey limestones, marlstones, sandy and quartzy limestones
E	Sandy, patchy, nodular, quartzy and chert limestones and silicites
E	Breccia limestones, shales and sandstones
D	Slates, sandstones, limestones, radiolarites, evaporites
D	Variegated slates, sandstones, dolomites, evaporites, Carpathian Keuper
D	Quartzites, sandstones, clayey shales, Lunz and Lower Triassic beds of Tatricum and Veporicum
D	Sandstones, calcareous shales, limestones, evaporites and Lower Triassic of Hronicum and Silicicum
	Upper Palaeozoic of the Central Western Carpathians
A	Shales, sandstones, conglomerates, acid volcanites, Upper Palaeozoic of Tatricum, Veporicum, Hronicum and Zemplinicum
B	Intermediary and mafic volcanites
B	Conglomerates, sandstones, shales, volcanites, carbonates
	Lower Palaeozoic of Gemericum
B	Prevailing sandstones, phyllites, mafic volcanites
B	Prevailing mafic volcanites
A	Prevailing metasandstones, phyllites and acid volcanites, carbonates, lydites
A	Prevailing acid volcanites

	Geochemical type of rocks
	Crystalline basement of Tatricum and Veporicum
A	Metapsammites, phyllites, micaschists, metavolcanites, carbonates
A	Gneisses to migmatites, phyllonites
B	Amphibolites, amphibolic gneisses
A	Prevailing acid to intermediary volcanites, Jánov grúň Complex
	Plutonites of the Central Western Carpathians
B	Diorites
A	Tonalites
A	Granodiorites to granites
A	Leucocratic granites
A	Gemeric granites

The information layer with areally divided five lithological types was covered with a layer with generated catchments areas (Fig. 5.1). The dominant lithotype was determined on the basis of the prevailing surface representation (percentage over 90%). Of course, many generated catchment areas did not meet this criterion.

The next step consisted of the separation of anthropogenically unaffected samples in five distinguished sets. It can be stated that the simplest qualitative criterion encompasses the content of chlorides, representing so-called conservative element owing to a high solubility of their compounds in the water. The initial rainwater, represented by the samples from the monitoring of snow pack quality, has an average concentration of chlorides 1.74 $mg \cdot l^{-1}$ with a maximum 45.2 $mg \cdot l^{-1}$ and 90^{th} quantile 4.01 $mg \cdot l^{-1}$. As a criterion, based on these results there was selected a wider border, less than 10 $mg \cdot l^{-1}$, and the best suited to 6 $mg \cdot l^{-1}$ of chlorides in the chemical composition of the surface water flow.

The result consisted of five sets of chemical composition of the surface water, divided according to environment of their formation. The total number of selected samples was 7,826, while the number of samples in individual files was not the same. In the group A, the number of samples was 1,631, in B 1,307, in C 2,472, in D 1,810 and the group E 642.

In terms of chemical composition, the surface water is characterized by the predominance of constituents Ca–HCO_3. In the cation composition there prevails the calcium content and in different representation in individual lithotypes there alternate magnesium and sodium. In the anion composition the bicarbonates dominate. The sulphates represent second most frequent component. In individual groups SiO_2 is represented in varying proportions. In general, these are the biggest differences in the chemical composition of the surface water. In contrast to the groundwater, the surface water is less variable, which can be observed in the domination of individual ions. This difference can be explained mainly by the shorter interaction (retention time) of the surface water with the environment, and thereby the preference of reactions with mineral phases, more soluble in the water, which run kinetically faster.

Despite certain monotony in chemical composition, there is possible to observe certain differences in the formation of the surface waters, related to the nature of the environment and the conditions of their formation. These differences and the genesis of surface water are interpreted in other parts of the text using various tools. There were used the descriptive statistics, correlation coefficients and the factor analysis with the software package STATISTICA, version 7. Descriptive statistical methods allow to

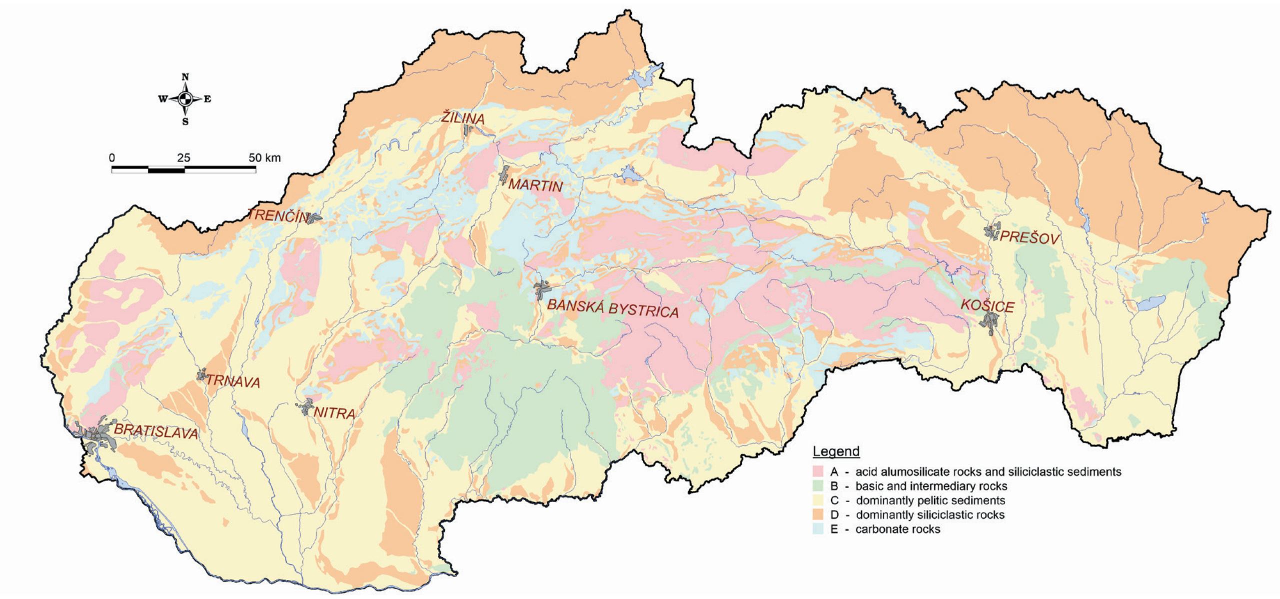

Fig.5.1 Allocated catchments areas of end members of the formation of chemical composition of the surface water.

compare mean values and the concentration range of selected ions in distinguished groups of surface water. Factor analysis facilitates the interpretation of the relationship between individual ions and allows to outline the main mineralisation processes in formation of the surface water. The extraction at the factor analysis was done by the method of main components. There was used the Varimax rotation type, the selection of the number of final factors was made using the scree-test. The ternary diagrams of the main cationic and anionic representation (used concentration unit was mmol·l^{-1}) were constructed using the HydroOffice software (Gregor, 2013). As to cations, diagrams are drawn up of calcium, magnesium and the sum of sodium with potassium, of anions there were bicarbonates, sulphates, chlorides and amounts of nitrates. These ions prevail in the chemical composition of the surface water in Slovakia. The interaction water–mineral phase was calculated by the program PHREEQC 3.0.6 (Parkhurst & Appelo, 1999) with a database of thermodynamic data *phreeqc*.

5.4 Formation of chemical composition of surface water

According to the conceptual model the formation of the chemical composition of the surface water is very complex mechanism. Moreover, the surface flow is open, dynamic, and it is affected by a large number of factors. A simplified approach represents the initial water – atmospheric precipitation (solid and liquid), which provides input for the formation of surface and groundwater. In this system it is clear that the natural conditions of Slovakia the interaction of water – rock – gas is the most important factor. The resulting chemical composition of surface water then most depends on the composition of the ground, altitude and climatic periods. The chemical composition of surface water quickly reacts to climatic period (spring snow melt, torrential rainfall, etc.), which leads to significant changes in water quality. Temporal changes in the chemical composition of surface water are not the topic of this paper (this is focus of the surface water quality monitoring).

Hereinafter, we will characterise five main types of end members of a surface water that are typical for Slovakia.

Surface water group A

The catchment areas of surface flows are mostly tied on acid alumosilicate rocks and siliciclastic sediments, as well as their metamorphic equivalents. They mostly represent the surface flows that are located in the upper parts of catchment areas (it is characteristic especially for crystalline massifs). Due to this fact and relatively inactive geological environment, their TDS is lowest of all distinguished groups. Calcium is the prevailing component in their cationic composition, in roughly similar representation there is magnesium and sum of sodium with potassium (Fig. 5.2).

In the anion composition there prevail bicarbonates, followed by sulphates and the sum of chlorides with nitrates (Fig. 5.3). The total mineralisation of the water varies within the range 8 – 192 mg·l^{-1} (Table 5.4), and especially in the upper parts of the catchment areas formed by the crystalline basement its chemical composition is similar to the groundwater present in these areas. It is interesting that in the case of higher representation of bicarbonates in

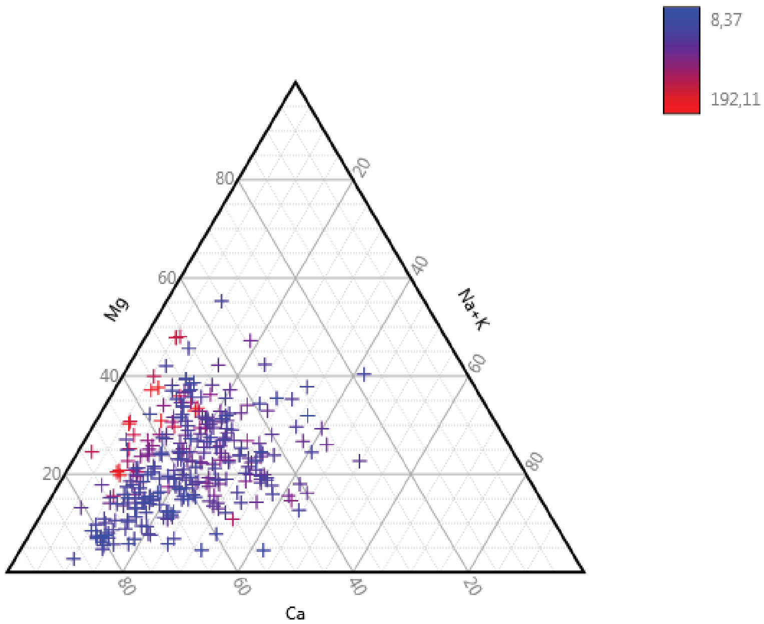

Fig.5.2 Cationic composition of surface water of the group A.

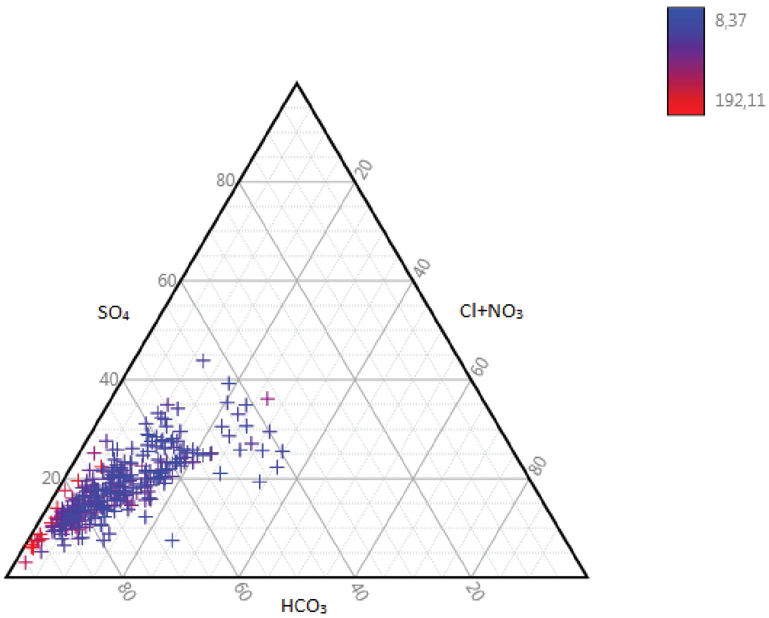

Fig.5.3 Anionic composition of surface water of the group A.

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the anion composition, their TDS increases (Fig. 5.3). At low TDS close to the minimum value, there is assumed a substantial proportion of virtually all major ions from the rainwater. This is the reason, why in comparison with other selected groups they have the lowest values of water hardness.

The summary of values of the chemical composition of surface water of the group A is stated in the Table 5.4. The certain anomalous concentration values are the values of the lower and upper quartiles. At the water with low TDS, the proportion of individual ions is quite variable and changes already at the small changes in concentration.

The final factor matrix consists of four factors (Table 5.5). The first factor manifests a high saturation of the sodium and silica. This factor is likely to constitute one of the most important mineralisation processes, namely the dissolution of the Na-plagioclase, with the accompanied release of Na and SiO_2 into water. The second factor is represented by the saturation by calcium, magnesium and sodium and can be interpreted as dissolution of Ca-plagioclases. Of course, other sources of these ions can be dissolved, e.g. micas and other present alumosilicate minerals of this rock environment. Scattered pyrite and its oxidation degradation are probably the source of the third factor. The

Tab. 5.4 The descriptive statistical parameters of surface water of the group A.

	Average	**Median**	**Minimum**	**Maximum**	**Lower quartile**	**Upper quartile**	**St. deviation**
pH	7.6	7.6	5.4	9.0	7.3	7.9	0.5
Na	3.23	2.80	0.02	17.30	1.80	4.10	2.14
K	1.07	0.76	0.05	17.50	0.40	1.48	1.12
Ca	13.18	11.72	1.60	38.88	8.02	17.64	6.60
Mg	4.09	3.55	0.10	14.52	2.33	5.47	2.49
Sr	0.074	0.050	0.010	5.400	0.037	0.070	0.260
Fe	0.090	0.036	0.004	4.660	0.016	0.080	0.223
Mn	0.029	0.005	0.001	7.000	0.003	0.014	0.229
NH_4	0.07	0.03	0.03	3.83	0.03	0.05	0.16
F	0.08	0.05	0.05	3.14	0.05	0.10	0.11
Cl	2.6	2.0	0.5	33.3	1.2	3.1	2.7
SO_4	19.2	16.7	1.0	114.0	12.0	24.2	11.5
NO_3	5.2	4.4	0.5	34.5	1.9	7.6	4.2
PO_4	0.05	0.02	0.02	2.80	0.02	0.04	0.13
HCO_3	39.48	33.55	1.22	121.43	20.14	52.48	24.25
SiO_2	11.22	9.96	0.83	58.07	7.61	12.54	6.10
Ca + Mg (mmol.l^{-1})	0.50	0.45	0.04	1.19	0.31	0.66	0.24
TDS	91.09	84.18	8.37	192.11	59.00	121.03	41.54

Note: Values besides pH are stated in mg.l^{-1}.

Tab. 5.5 Factor matrix – surface water of the group A.

	Factor 1	**Factor 2**	**Factor 3**	**Factor 4**
pH	–0.196	0.497	–0.148	0.500
Na	**0.769**	0.253	0.121	0.382
K	0.648	0.251	0.117	0.399
Ca	0.075	**0.883**	0.078	0.201
Mg	0.150	**0.770**	0.186	0.328
Sr	0.103	0.616	–0.074	–0.307
Fe	0.045	0.058	**0.855**	0.009
Mn	0.094	0.069	**0.840**	0.063
NH_4	0.240	–0.095	0.029	0.124
F	0.612	–0.008	0.132	–0.152
Cl	0.345	0.136	0.094	0.646
SO_4	0.427	0.499	0.234	0.410
NO_3	0.142	–0.027	0.042	**0.807**
PO_4	0.314	0.033	–0.136	0.227
HCO_3	0.011	**0.916**	0.057	–0.028
SiO_2	**0.787**	0.110	–0.017	0.006

fourth factor represents the high saturation of nitrate. The forms of nitrogen and its role in the formation of this water were discussed in the previous section. In the group A it represents a nitrogen form of natural origin, which source is mainly biomass.

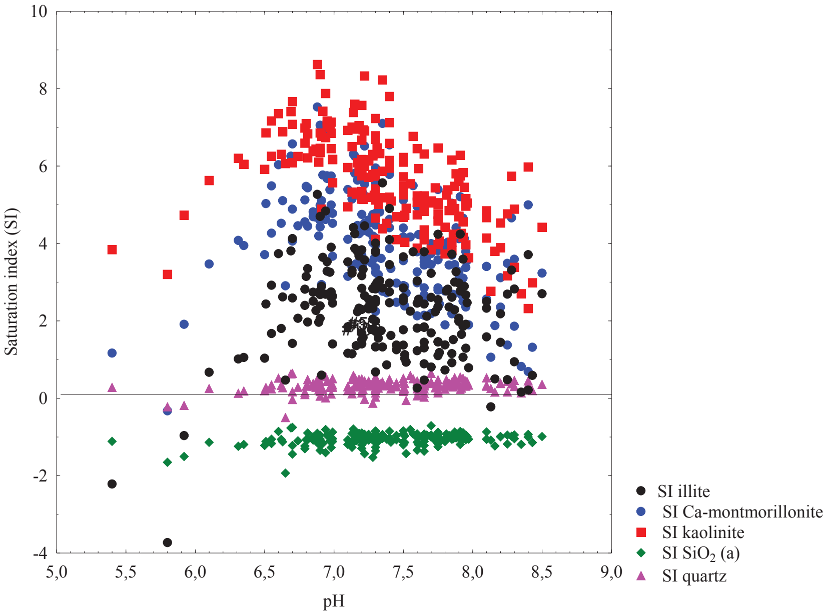

Fig. 5.4 Saturation index of selected mineral phases.

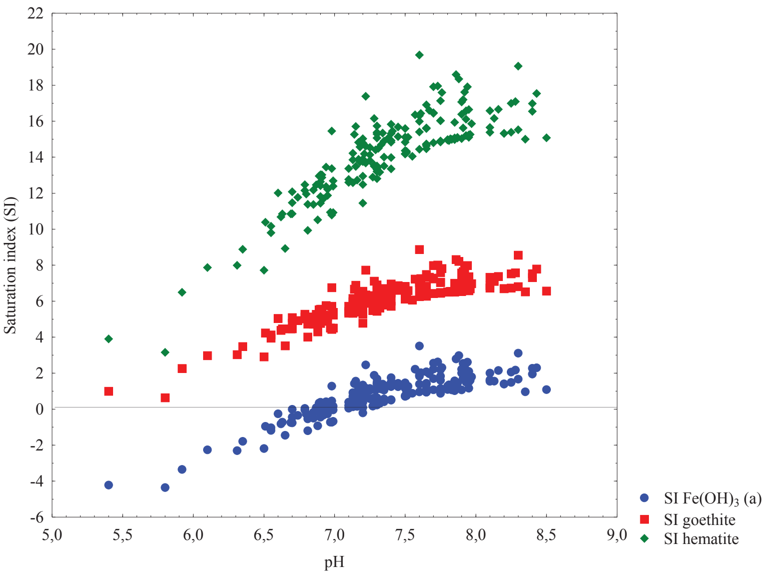

Fig. 5.5 Saturation index of selected mineral phases.

In terms of thermodynamic equilibrium there are interesting the weathering products of alumosilicate minerals. Saturation index of selected plausible mineral phases (Fig. 5.4) documents that amorphous quartz in solution is not sufficiently saturated, but a substantial part of quartz is more or less in equilibrium with the surface water. At higher pH values it may lead to oversaturation. By contrast, kaolinite, montmorillonite and Ca-illite mineral phases are supersaturated and will fall out of solution.

In terms of iron minerals (Fig. 5.5) its trivalent form (in flows the oxidizing environment is prevailing), the amorphous ferric hydroxide is not sufficiently saturated below a pH range of about 7.5 in a solution, resp. it is in equilibrium, and above pH 7.5 it becomes oversaturated and in the surface water it will be most likely in colloidal form. Saturation indexes of hematite and goethite indicate oversaturation of these mineral phases.

The surface water of this group may be in the groundwater genetic classification by Gazda (1971, 1974) classified as silicatogene. This water is mainly formed by interactions of the water with alumosilicate minerals. A proportion of mainly low-mineralised surface water can have a relatively large share of major ions from atmospheric precipitation.

Surface water of the group B

This group of surface water is linked to the catchment area built of basic and intermediary rocks. They represent the surface flows which chemical composition of the water is mainly formed in the environment of Neogene volcanic complexes. Their cationic composition (Fig. 5.6) is characterized by a predominance of calcium ions, presence of magnesium in the range of 40 – 60% and the sum of sodium and potassium 20 – 40%.

In the anion composition the bicarbonates are dominating, in this case it is the highest TDS in the surface water of this group (Fig. 5.7). A relatively large proportion of this water contains a lower amount of bicarbonates, present are the remaining major anions. It is characteristic especially at the lowest levels of TDS.

The overview of the chemical composition of the surface water of the B group is in Table 5.6. In addition to the above stated representation of the main ions, this water is different from all selected groups by the highest concentration of SiO_2. It can be assumed that this is caused by the low stability of rock-forming minerals (indicatively it is governed by the reverse Bowen reaction scheme) in their environment at the weathering processes. In comparison with the surface water A and C, the SiO_2 content in group B is up to three times higher. In terms of TDS from the aforementioned reasons, the surface water of Neogene volcanic complexes have higher values than the water bound to the crystalline rock environment.

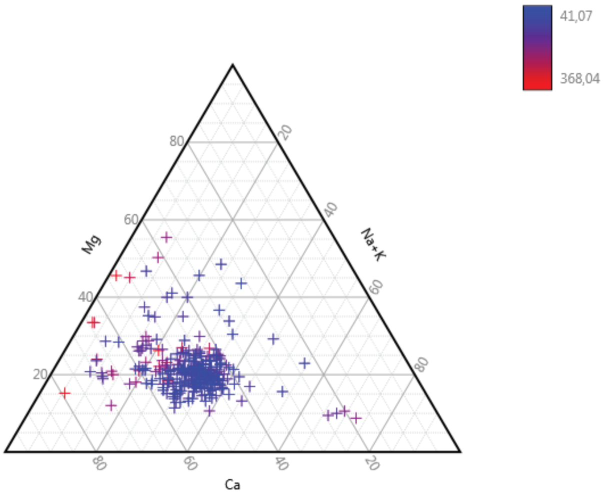

Fig. 5.6 Cationic composition of the surface water of the group B.

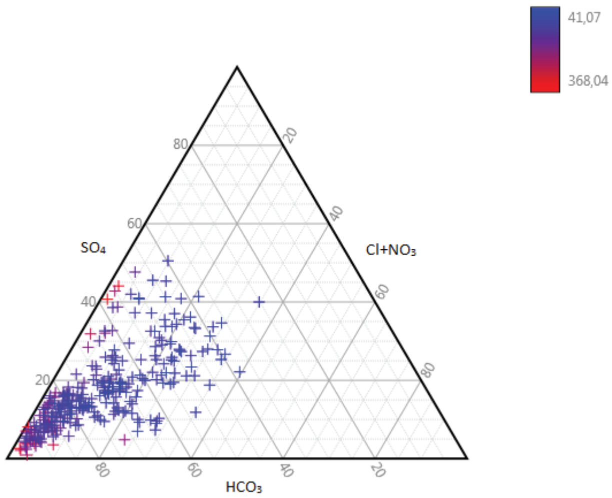

Fig. 5. 7 Anionic composition of the surface water of the group B.

Tab. 5.6 The descriptive statistical parameters of the B group surface water.

	Average	Median	Minimum	Maximum	Lower quartile	Upper quartile	St. deviation
pH	7.7	7.7	3.5	9.4	7.4	8.0	0.5
Na	5.11	4.60	0.60	31.50	3.16	6.22	3.01
K	2.10	1.90	0.05	10.19	1.21	2.66	1.26
Ca	20.71	17.23	3.35	103.81	12.42	23.82	12.92
Mg	5.87	4.79	1.30	64.16	3.16	6.98	4.59
Fe	0.196	0.069	0.004	4.242	0.028	0.230	0.341
Mn	0.031	0.008	0.001	1.644	0.003	0.026	0.100
NH_4	0.09	0.03	0.03	1.78	0.03	0.08	0.14
F	0.08	0.05	0.05	1.63	0.05	0.08	0.09
Cl	2.3	2.3	0.5	4.4	1.5	3.2	1.0
SO_4	25.4	19.9	2.2	309.0	12.8	30.8	24.7
NO_3	4.6	3.6	0.5	40.4	1.5	7.0	4.1
HCO_3	71.62	57.97	3.66	341.09	36.60	97.65	49.17
SiO_2	30.51	30.73	2.62	137.00	21.80	39.49	14.75
Ca + Mg ($mmol \cdot l^{-1}$)	0.76	0.62	0.21	3.39	0.44	0.87	0.47
TDS	143.77	123.41	41.07	368.40	92.27	170.39	75.61

Note: Values besides pH are stated in $mg \cdot l^{-1}$.

In the case of surface water of the B group, the final factor structure is represented by four factors (Table 5.7). The first factor expresses the high saturation of pH, calcium, magnesium, and bicarbonate. It represents own conditions of a bicarbonate equilibrium in surface water. It is the dominant system, even though the carbonates in the rock environments are absenting and calcite, dolomite and aragonite are according to thermodynamic model unsaturated mineral phases. Thus, the source of the individual members of the carbonate equilibrium are other minerals, mainly plagioclase, pyroxene, etc., as well as the carbon dioxide.

In the second factor there is dominating the positive saturation of sodium, potassium, and silica (expressed as SiO_2). It can be assumed that this factor reflects the hydrolytic degradation of silicates. The third factor represents the high saturation of iron and manganese, which enhances their presence in surface water of the B group. The fourth factor represents the sulphate saturation, which enters this environment through the oxidative degradation of the sulphides.

In terms of the interaction water-mineral, amorphous aluminium hydroxide in this system represents prevailingly unsaturated mineral phase, eventually the mineral phase in equilibrium (Fig. 5.8). By contrast, the gibbsite and kaolinite are in the whole pH range of the values the oversaturated and from the water they will probable precipitate in the form of colloidal parts.

Tab. 5.7 Factor matrix - surface water of the group A.

	Factor 1	Factor 2	Factor 3	Factor 4
pH	**0.737**	–0.046	–0.154	–0.210
Na	0.072	**0.748**	0.041	0.461
K	0.010	**0.738**	0.479	–0.045
Ca	**0.701**	0.128	0.029	0.568
Mg	**0.754**	–0.019	0.022	0.430
Fe	–0.112	0.065	**0.798**	–0.022
Mn	0.076	–0.024	**0.782**	0.130
NH_4	0.022	0.129	0.699	–0.002
F	0.155	0.315	0.015	0.181
Cl	0.067	0.080	0.240	0.591
SO_4	0.139	–0.041	–0.159	**0.847**
NO_3	–0.169	–0.546	0.079	0.033
HCO_3	**0.846**	0.297	0.163	0.224
SiO_2	–0.240	**0.816**	0.149	–0.171

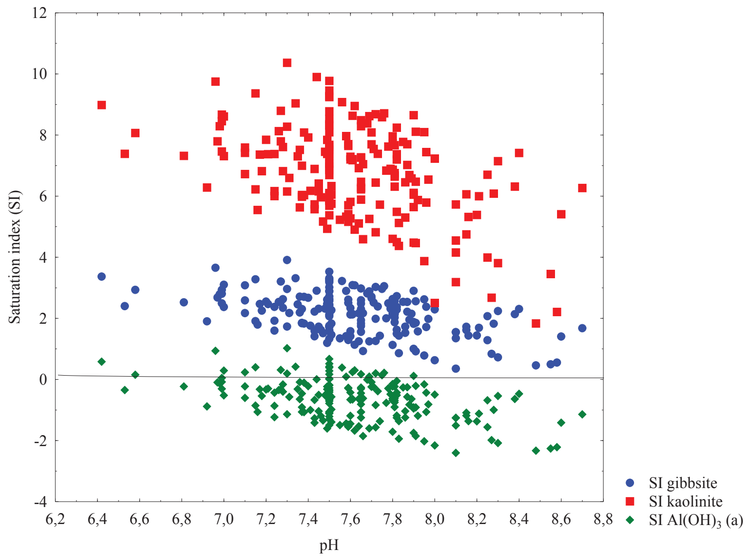

Fig. 5.8 Saturation index of selected mineral phases.

Surface water of the group C

The environment of the surface water generation of this group is built mostly of pelitic sediments. They have specific characteristics, both in terms of permeability, as well as the creation of a complex system of interaction water-mineral phases. The pelitic sediments have variable amounts of carbonate cement and, therefore, their chemical composition to some extent corresponds to that in the surface water of D group. The cationic representation in the surface water of C group has an interesting distribution (Fig. 5.10), which can be simply divided into two areas. The first is characterized by higher values of the total dissolved solids and prevalence of calcium and magnesium ions. The second area is represented by a larger pro-

Hematite, goethite, amorphous ferric hydroxide are oversaturated in this group of surface water (Fig. 5.9). The amorphous silica is an undersaturated mineral phase, but silica is prevailingly oversaturated, eventually it is in equilibrium.

The above data indicate that the surface water of the B group, similarly as A group, in terms of genetic classification, is silicatogene. Its characteristic feature is represented by the ratio of different ions, higher values of total dissolved solids and the highest SiO_2 content among all groups of surface waters.

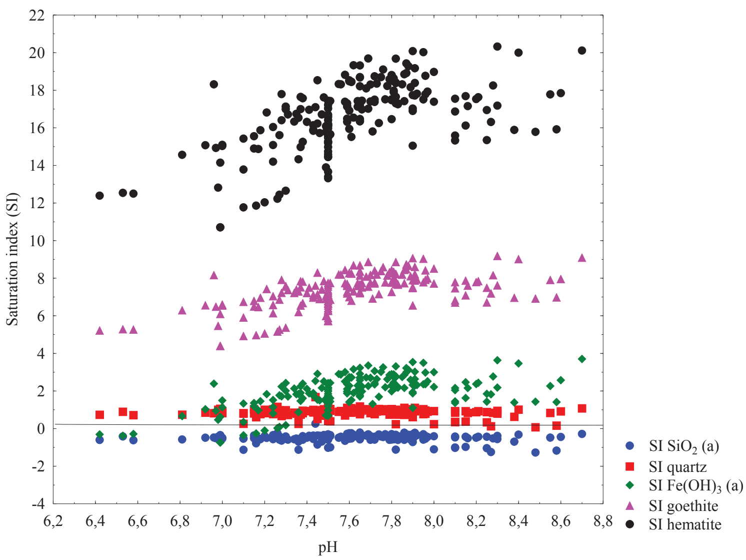

Fig. 5.9 Saturation index of selected mineral phases.

portion of the sum of sodium and potassium. It can be said that the first area probably represents the rock environment with a higher content of calcareous cement in sediments. The second area is obviously characterized by a smaller proportion of calcareous cement and the water formation is more influenced by the ion exchange reaction. In anionic composition of the surface water of the C group the bicarbonates are dominating, next there follow sulphates and a sum of chlorides with nitrates (Fig. 5.11). Water with a characteristic bicarbonate content manifests the highest TDS. It means that distinct Ca(Mg)–HCO_3 chemical types have the highest total dissolved solids, which is in compliance with above stated part with dominant representation of calcium and magnesium.

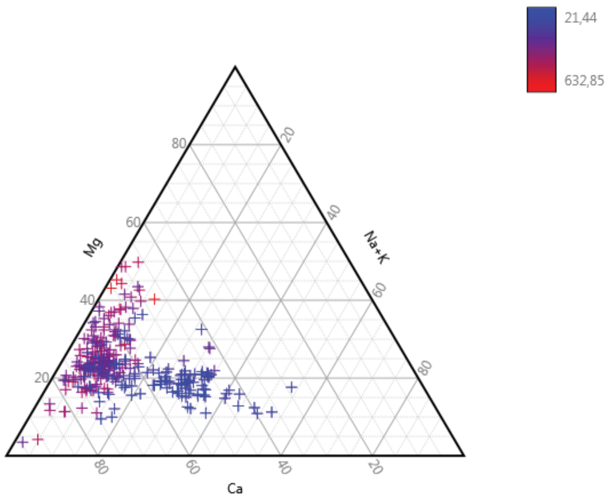

Fig. 5.10 Cationic composition of the surface water of the group C.

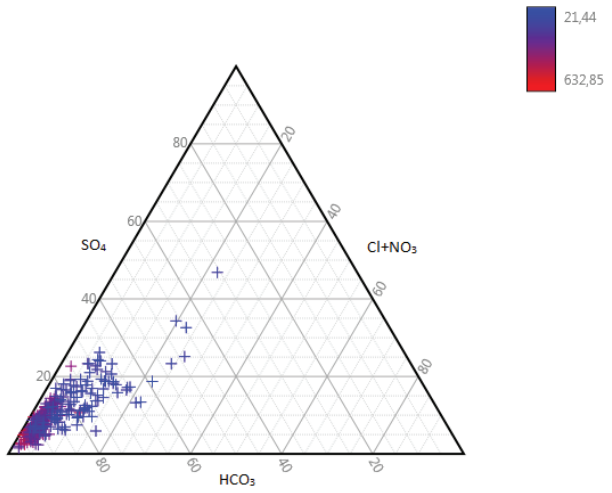

Fig. 5.11 Anionic composition of the surface water of the group C.

Tab. 5.8 The descriptive statistical parameters of the surface water of the group C.

	Average	Median	Minimum	Maximum	Lower quartile	Upper quartile	St. deviation
pH	8.0	8.1	6.2	9.5	7.8	8.3	0.4
Na	4.45	4.10	0.40	24.70	2.80	5.53	2.65
K	1.59	1.30	0.10	8.80	0.80	2.00	1.20
Ca	53.70	56.50	3.52	142.68	26.67	76.34	28.95
Mg	13.46	11.67	0.59	49.13	6.18	17.91	9.39
Sr	0.220	0.180	0.020	0.830	0.100	0.310	0.149
Fe	0.176	0.077	0.004	3.518	0.034	0.180	0.316
Mn	0.028	0.010	0.001	1.770	0.005	0.027	0.082
NH_4	0.12	0.03	0.03	2.52	0.03	0.13	0.23
F	0.12	0.10	0.05	0.88	0.05	0.13	0.10
Cl	3.4	3.0	0.5	7.2	1.9	4.8	1.8
SO_4	29.8	27.2	4.0	193.2	16.7	38.9	18.2
NO_3	4.5	3.4	0.5	33.9	1.6	5.7	4.3
PO_4	0.07	0.02	0.02	0.77	0.02	0.08	0.11
HCO_3	193.42	201.30	4.27	454.45	90.30	281.76	109.06
SiO_2	11.44	7.91	0.35	84.10	6.12	12.70	9.95
Ca + Mg (mmol.l^{-1})	1.89	1.97	0.11	4.24	0.93	2.76	1.03
TDS	306.94	320.56	21.44	632.85	163.29	443.09	158.20

Note: Values besides pH are stated in mg.l^{-1}.

The statistical characteristics of the chemical composition of the surface water of C group are documented in Table 5.8. The chemical composition is similar to the surface water of the group D, but it has a higher mean value of TDS, different ratios of the main cations and higher content of SiO_2. This similarity results from the high variability of the rock environment of both selected groups of the surface water. This is documented e.g. by large differences in minimum and maximum total dissolved solids (Table 5.8).

The resulting factor structure of the surface water of C group includes three factors (Table 5.9). The first represents a high positive saturation by calcium, magnesium and bicarbonates. This factor represents dissolution of the carbonate cement, as well as varying amounts of carbonates in these sediments. The resulting product of interactions represent significant Ca(Mg)–HCO_3 types of surface water. The second factor is represented by the high saturation of sodium and potassium. Presumably, that is a reflection of the ongoing processes of ion exchange, where from the sorption complex of the clay minerals Na and K enter into a solution. The last factor with a strong representation of iron and manganese indicates the source of these elements in the form of scattered minerals in sediments.

Tab. 5.9 Factor matrix - surface water of the group C.

	Factor 1	**Factor 2**	**Factor 3**
pH	0.552	–0.023	–0.157
Na	0.094	**0.861**	0.047
K	0.135	**0.774**	0.119
Ca	**0.931**	0.022	0.001
Mg	**0.844**	0.009	–0.085
Fe	–0.071	0.025	**0.872**
Mn	–0.063	0.042	**0.841**
NH_4	0.015	0.161	0.466
Cl	0.500	0.546	0.212
SO_4	0.675	0.268	–0.134
NO_3	0.452	0.024	0.143
HCO_3	0.927	0.009	–0.010
SiO_2	–0.414	0.614	0.090

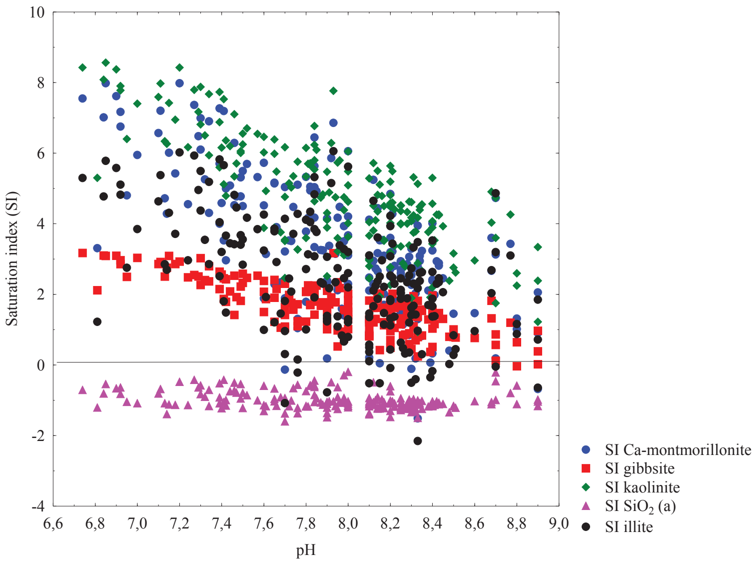

Fig. 5.12 Saturation index of selected mineral phases.

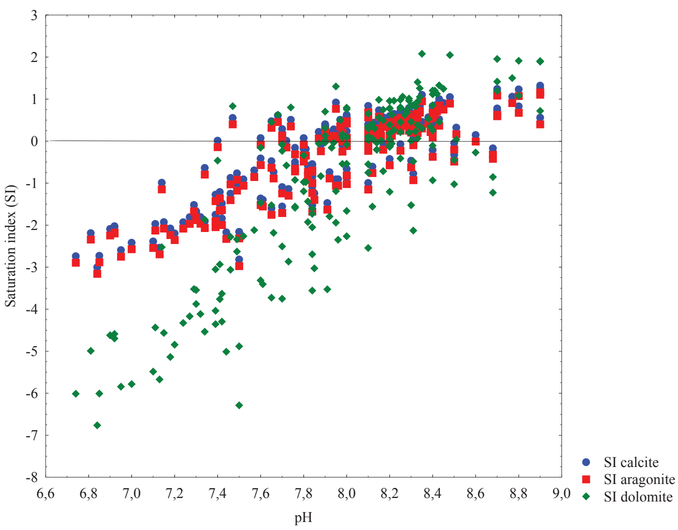

Fig. 5.13 Saturation index of selected mineral phases.

Regarding the saturation index of carbonate mineral phases versus pH measurements (Fig. 5.12) it is interesting that part of the water is saturated with calcite, dolomite and aragonite. This concerns the surface water in the environment of sediments with calcareous cement, resp. presence of carbonate minerals. Because their permeation is buffered by the rainwater of acid character, into surface water there is deliberated Ca, Mg and HCO_3. Obviously, the oversaturation of carbonate mineral phases increases with increasing pH value (Fig. 5.12).

The only plausible phase from the clay minerals, which is oversaturated in the whole interval of pH values, is a kaolinite. The calculated saturation indexes of Ca-montmorillonite and illite (Fig. 5.13) indicate that with increasing pH value they are lower, or in some cases they are in equilibrium with the water. Gibbsite typically is the first mineral phase, which is oversaturated in the process of silicate weathering. This is also in respect to this surface water. Insufficiently saturated mineral phase in this group is represented by amorphous SiO_2.

From the above assessment, there can be concluded that in surface waters bound predominantly to pelitic sediments the chemical composition is partially formed by the water interaction with carbonatic minerals, ion exchange processes and oxidative degradation of pyrite. In terms of genetic classification of the water, there can be said that it is of carbonatogene-hydrosilicatogene type.

Surface water of the group D

It represents a selected group of surface water bound to the catchment areas, formed prevailingly by the siliciclastic rock environment.

Regarding to the cationic representation (Fig. 5.14), this water has the supreme Ca content (60 – 80%), Mg (prevailingly 20 – 40%) and Na + K sum up to 20%. In their anionic composition (Fig. 5.15) the bicarbonates fully prevail (more than 80 %), next there follow sulphates and a sum of Cl and NO_3. The highest values of total dissolved solids exhibits a water with predominant representation of bicarbonates and increased content of sulphates.

The general chemical composition of the D group surface water is documented in Table 5.10. The TDS of the water varies in a wide diapason, 23 – 521 mg·l^{-1}. It is mainly due to a high variability of the rock environment in the catchment area. It consists of relatively inactive lithogeochemical composition from sandstone to gravels, characterized by a varying degree of calcium content. Therefore, in an environment of sandstones the values

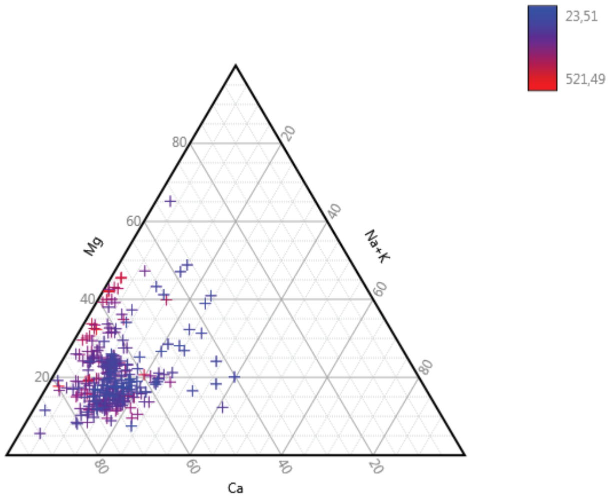

Fig. 5.14 Cationic composition of the surface water of the group D.

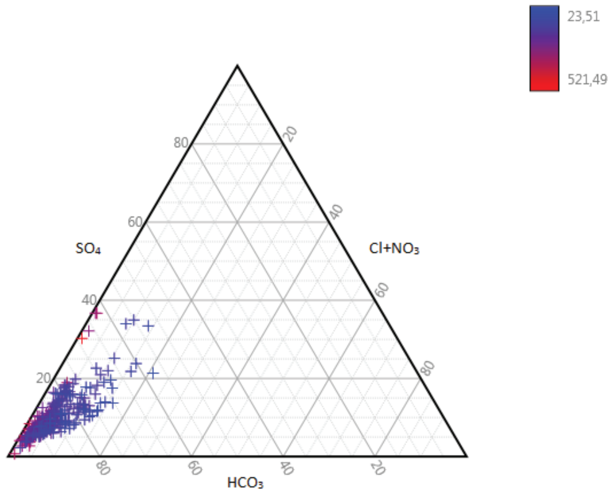

Fig. 5.15 Anionic composition of the surface water of the group D.

Tab. 5.10. The descriptive statistical parameters of the surface water of the group D.

	Average	Median	Minimum	Maximum	Lower quartile	Upper quartile	St. deviation
pH	8.1	8.1	4.6	9.4	7.9	8.3	0.4
Na	4.85	4.35	0.19	16.90	2.70	6.57	2.91
K	1.38	1.20	0.05	5.51	0.88	1.70	0.79
Ca	47.25	46.33	2.98	179.56	30.46	62.91	21.55
Mg	8.86	7.04	0.32	36.48	4.65	11.22	6.12
Sr	0.282	0.251	0.018	0.990	0.111	0.384	0.205
Fe	0.119	0.043	0.004	6.309	0.020	0.101	0.355
Mn	0.021	0.007	0.001	3.010	0.003	0.015	0.107
NH_4	0.08	0.03	0.03	0.84	0.03	0.08	0.10
F	0.09	0.05	0.05	1.02	0.05	0.10	0.10
Cl	2.3	2.1	0.5	4.4	1.6	2.9	0.9
SO_4	26.6	23.7	2.5	160.7	19.1	30.4	15.2
NO_3	3.6	2.8	0.5	22.3	1.8	4.7	2.7
PO_4	0.04	0.02	0.02	1.07	0.02	0.04	0.07
HCO_3	158.75	154.99	9.76	372.21	99.46	215.39	74.81
SiO_2	7.42	6.98	0.40	29.30	5.69	8.36	3.13
Ca + Mg (mmol.l^{-1})	1.54	1.47	0.10	4.78	0.99	2.05	0.71
TDS	254.90	249.07	23.51	521.49	166.35	342.72	110.64

Note: Values besides pH are stated in mg.l^{-1}.

of mineralisation are the lowest and in sandy and gravel sediments the highest. From the hydrogeochemical viewpoint there runs probably the most intense infiltration, resp. the draining effect of the surface flow, depending on the season and rainfall. On the water of surface flows the greatest impact has an infiltration, or drainage effect, which the most intensively changes the chemical composition of the surface water. In many cases, its composition corresponds to that of the groundwater. Stated wide range of TDS values, of course, causes a high variability in other components, most in the case of calcium, bicarbonates and sulphates.

Interrelations between different selected components are documented by resulting factor structure (Table 5.11). The first factor is characterized by a high saturation of calcium, magnesium, and bicarbonate. It can be explained by the process of carbonates dissolution, which is probably the most significant process of formation of this group of surface water. The second factor represents a saturation of sodium and potassium and apparently is a common source of these cations. Regarding the environment of this water formation, it can be supposed that it will be a product of the hydrolytic decomposition of silicates. Third factor, being represented by the iron and manganese saturation, is characteristic for virtually all selected groups of surface water. It results from the geological conditions of the Western Carpathians, where almost all lithogeochemical types involve the above elements. The significant is that in the groundwater they are in a dissolved form owing the creation of local reducing conditions in the aquifer and in the surface water there occurs the oxidation by atmospheric oxygen. The fourth factor has a high negative saturation of nitrates, which demonstrates that they are involved to a minimum degree in the chemical composition of the surface water. With this consideration we should bear in mind that the

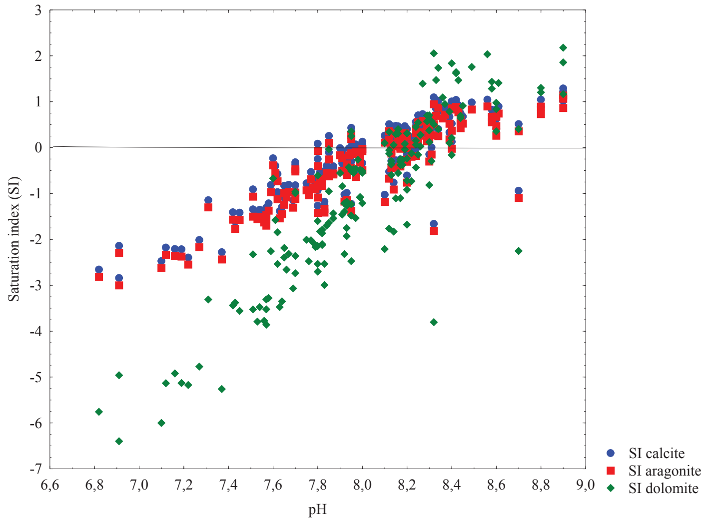

Fig. 5.16 Saturation index of selected mineral phases.

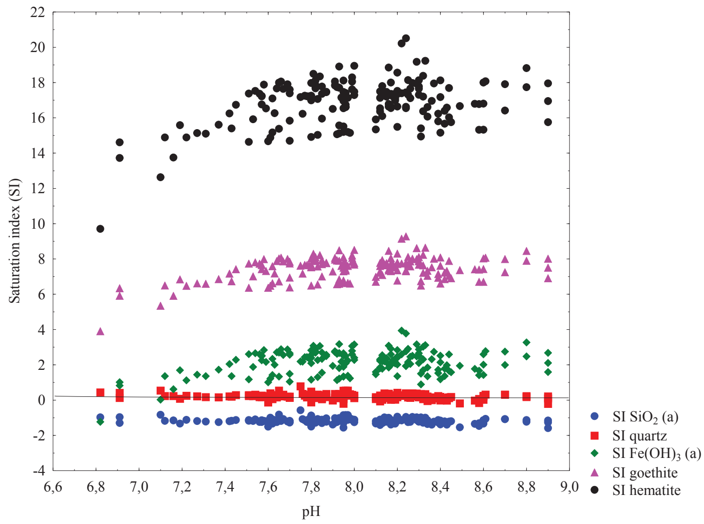

Fig. 5.17 Saturation index of selected mineral phases.

Tab. 5.11 Factor matrix - surface water of the group D.

	Factor 1	Factor 2	Factor 3	Factor 4
pH	0.408	0.023	–0.042	–0.112
Na	0.215	**0.786**	0.040	0.323
K	0.157	**0.833**	0.067	0.156
Ca	**0.871**	0.292	–0.011	0.111
Mg	**0.839**	–0.109	0.009	–0.141
Fe	–0.066	–0.014	**0.815**	0.090
Mn	–0.041	0.001	**0.810**	0.016
NH_4	0.107	0.220	0.330	–0.169
Cl	0.468	0.652	0.090	–0.122
SO_4	0.624	0.214	0.000	–0.112
NO_3	0.174	–0.090	–0.007	**–0.852**
HCO_3	**0.891**	0.202	0.045	0.136
SiO_2	–0.103	0.652	–0.018	–0.379

selection was done by the way to exclude the input of anthropogenically polluted water.

The thermodynamic analysis supplements the results of the factor matrix. In the case of the carbonate balance, calcite, aragonite and dolomite in the solution are oversaturated at a pH values higher than 8 (Fig. 5.16). Undersaturation of other samples of the surface water may be due to the higher pressure of carbon dioxide and the lack of carbonate minerals in the environment of their origin.

Concerning the iron mineral phases, the amorphous ferric hydroxide as well as goethite and hematite are oversaturated in the solution (Fig. 5.17). By contrast, all surface waters are undersaturated by amorphous SiO_2, and in respect to the quartz they are in equilibrium.

From the genetic point of view, the surface water of the D category bound to siliciclastic geological environment can be described as carbonatogene-silicatogene. The main mineralising processes, producing its chemical composition, encompass the dissolution of carbonates and hydrolytic decomposition of silicate minerals.

Surface water of the group E

The surface water of this group is bound to the catchment areas made up mainly of carbonate rocks. It is also reflected in its chemical composition, which is different from that of the other groups of surface water. In its cationic composition (Fig. 5.18), the calcium is the most abundant and magnesium represents the second main ion. The sum of Na and K is represented only minimally, it is the lowest of all distinguished groups of surface water. The ratio of Mg/Ca has an average value of 0.49, with a minimum value of 0.03 and the maximum 2.43. This ratio depends on the representation of limestone and dolomite in the catchment area. When the value of this ratio is about 0.5, the environment contains approximately the same proportion of limestone and dolomite, at 0.75 and more dolomites prevail and a ratio 0.3 and less is typical for the environment of limestones. Fig. 5.30 demonstrates that any small increase in the sum Na and K causes the decrease in the total dissolved solids of surface water of the E group. It is probably caused by a certain proportion of the clayey limestones in the rock environment, which in interaction with water deliberate the sodium and potassium ions into solution, while the Ca and Mg content in comparison with limestones is lower. In anionic composition there dominate the bicarbonates, the second most represented anions are sulphates (Fig. 5.19). The source of sulphates in the surface water represent the gypsum in the rock environment of the basin.

The chemical composition of surface water is documented in Table 5.12. The greatest variability of cations has a calcium content, which is probably related to the time of the contact with the groundwater, temperature and partial pressure of CO_2 in the water of surface flow, as well as to the mineral composition in the rock environment. Similar relation is manifested at minimum and maximum values of pH and bicarbonates. The lowest concentration of SiO_2 from all classes of the surface water is related mainly to its low content in the rock environment of carbonate sediments. Significantly different, and the highest is the hardness value of the water, expressed as the sum of Ca and Mg. Similarly, within the selected catchment areas according to prevailing lithogeochemical types there can be stated that in the environment of carbonates the surface water has the highest mean values of total dissolved solids. Environment with a predominance of carbonate rocks also represent rocks with the highest buffer capacity in relation to acid precipitation.

The resulting factor structure of the surface water of the E group contains three factors (Table 5.13). The first is represented by a high saturation of calcium, magnesium and bicarbonate. It can be explained by the interaction of water–carbonates, representing the main mineralisation process in this water group. The second factor represents the high saturation of sodium and potassium. A common source of these elements in the surface water can be a hydrolytic decomposition of silicate minerals, present mainly in sandy limestones. It must be emphasized that regarding the small presence of these rocks, these processes in carbonate environments are not dominant.

For this group of surface water in terms of the thermodynamic analysis, the most significant is the relation between the balance of the carbonate mineral phases, pH and gypsum (Fig. 5.20). Gypsum represents a mineral phase undersaturated in the water, which follows from the above stated characteristics of the water forming environment. By contrast, calcite, aragonite and dolomite at a particular pH range higher than 8.2 occur in equilibrium with these minerals, resp. they are oversaturated. This equilibrium state was found at a simple majority of surface waters, allocated to the group E. It is interesting that despite the lowest silica concentration in all distinguished groups of surface water, it is detected in equilibrium in the whole range of pH values (Fig. 5.21). At Ca-montmorillonite and illite there can be stated that in the mild acid to neutral environments they are oversaturated in solution (Fig. 5.21).

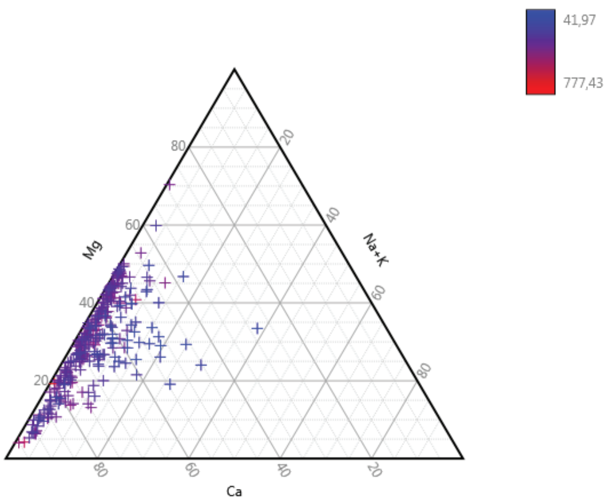

Fig. 5.18 Cationic composition of the surface water of the group E.

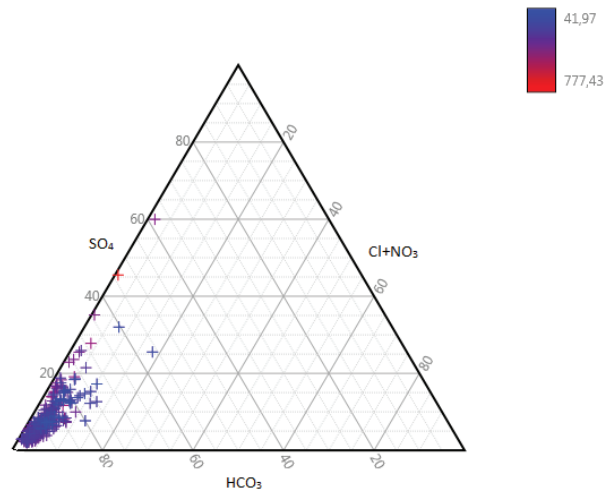

Fig. 5.19 Anionic composition of the surface water of the group E.

In slightly alkaline environment their stability is divided to undersaturated part (obviously from the environment of pure limestones and dolomites) and oversaturated part.

Overall, we can state that the surface water is formed in parts of the catchment areas, built mainly by carbonates, by the dissolution of limestones and dolomites, less of gypsum. From a genetic point of view, this water can be regarded as carbonatogene and to a much lesser extent as sulphatogene. Less significant process, forming the chemical composition of this group of surface water, is a hydrolytic decomposition of silicate minerals.

Tab. 5.12 The descriptive statistical parameters of the surface water of the group E.

	Average	Median	Minimum	Maximum	Lower quartile	Upper quartile	St. deviation
pH	8.2	8.3	6.7	9.0	8.0	8.4	0.3
Na	1.69	1.20	0.10	9.96	0.70	2.11	1.50
K	0.76	0.60	0.05	11.00	0.32	0.90	0.82
Ca	58.03	58.06	4.41	174.79	44.60	71.33	23.50
Mg	15.62	14.20	1.84	46.50	8.76	21.60	8.70
Sr	0.225	0.120	0.010	3.380	0.057	0.250	0.340
Fe	0.061	0.025	0.004	1.348	0.011	0.055	0.112
Mn	0.009	0.003	0.001	0.260	0.003	0.006	0.023
NH_4	0.06	0.03	0.03	1.40	0.03	0.05	0.10
F	0.11	0.05	0.05	0.79	0.05	0.11	0.12
Cl	2.4	2.0	0.5	7.1	1.4	3.0	1.5
SO_4	30.6	24.8	3.9	326.8	16.7	36.8	25.3
NO_3	5.4	4.6	0.5	27.5	2.3	7.3	4.1
PO_4	0.04	0.02	0.02	2.50	0.02	0.03	0.12
HCO_3	205.63	208.68	18.31	397.00	161.70	250.17	77.24
SiO_2	5.43	4.93	0.15	24.76	3.12	6.62	3.49
Ca + Mg (mmol.l^{-1}l)	2.09	2.13	0.24	5.41	1.70	2.53	0.75
TDS	323.23	325.54	41.97	777.43	255.91	391.89	113.99

Note: Values besides pH are stated in mg.l^{-1}.

Tab. 5.13 Factor matrix – surface water of the group E .

	Factor 1	Factor 2	Factor 3
pH	0.340	–0.287	–0.243
Na	0.008	**0.789**	0.342
K	0.047	**0.756**	–0.039
Ca	**0.817**	0.190	–0.016
Mg	**0.715**	–0.170	0.058
Fe	0.093	0.044	**0.790**
Mn	0.113	0.233	**0.753**
Cl	0.455	0.653	0.060
SO_4	0.492	0.131	0.196
NO_3	0.299	0.460	–0.359
HCO_3	**0.886**	0.061	–0.018
SiO_2	–0.188	0.682	0.293

5.5 Isotopic composition of oxygen and deuterium in the surface water

The water in surface flows in Slovakia is a product of precipitation, as evidenced by its isotopic composition. It originates directly from the precipitation, as well as from the groundwater. The share of the groundwater, having different than the meteoric origin, is negligibly small in the surface flows of Western Carpathians. On the territory of Slovakia there are known several groundwater sources of marine origin, bitter brines resources associated with the oil and gas occurrences, as well as the sources with a ratio of the groundwater originating during the complicated conditions in buried flysch units. Though, they have a minimum yield and have virtually no impact on the composition of surface water flows.

Under standard conditions, the isotopic composition of the natural water molecule retains its principal characteristics even in different environments. It means that the surface water flows should reflect the distribution of isotopes in precipitations, as well as derived groundwater, which

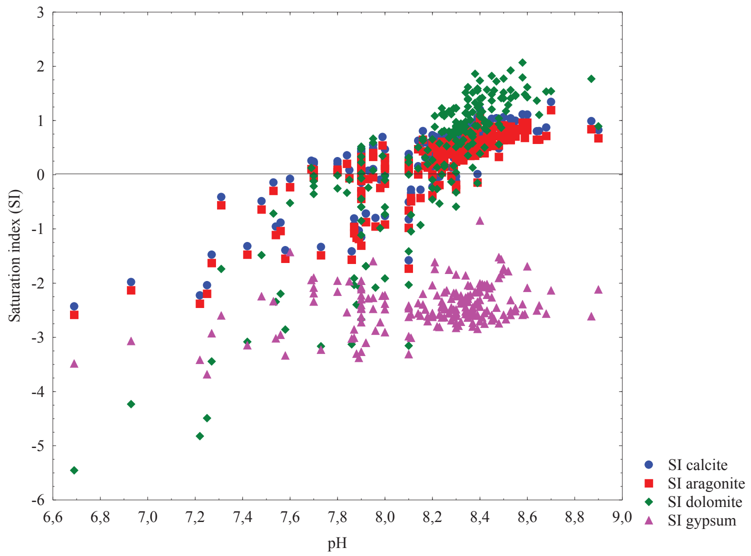

Fig. 5.20 Saturation index of selected mineral phases.

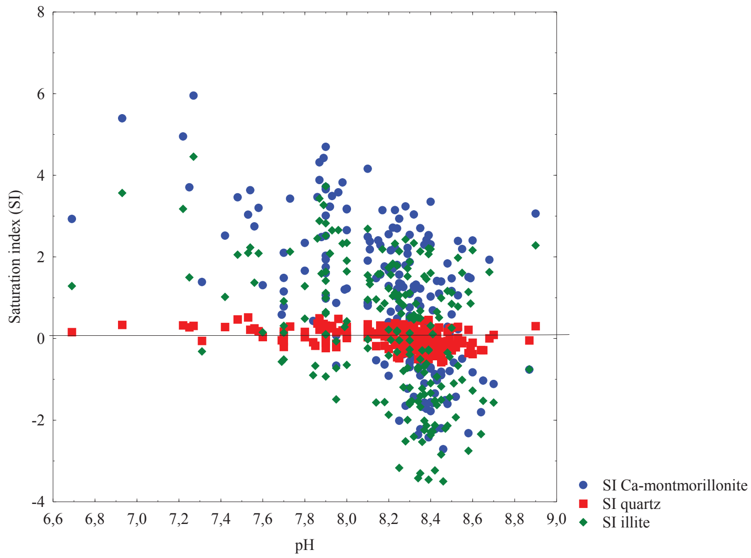

Fig. 5.21 Saturation index of selected mineral phases.

could take part in formation of surface water. The distribution of oxygen and hydrogen isotopes in precipitations depends mainly on the temperature, and thus the altitude in which precipitations fall, resp. it depends on the altitude of the relevant hydrogeological structure catchment and in our conditions also on the year season. The representation of lighter isotopes of both elements with decreasing temperature correspondingly increases, water is isotopically lighter, depleted, and the δ values are more negative.

Isotopic composition of 55 water samples of the main water flows (sampling date 5.–10. 8. 2013) has a relatively large spread, $\delta^{18}O$ from –6.84 to –12.09 ‰, $\delta^{2}H$ from –47.6 to –87.7 ‰. Average values ($\delta^{18}O$ = –9.90 ‰ and $\delta^{2}H$ = –71.7 ‰) converge to average δ values from precipitations in Slovak territory. Water in all documented water flows is unambiguously of the meteoric origin. It is evidenced by the position of the projection points of the samples in the vicinity of the global meteoric water line (GMWL) in Fig. 5.22. In some rivers, especially in southern Slovakia (Bodva, Bodrog, Ipeľ, Nitra and Slaná rivers) and in the Morava River the water is apparently influenced by evaporation. These rivers in warm climates are mostly slowly flowing; they are influenced also by the surface reservoirs in which the water circulation is slower, and the water surface is larger. In order to assess whether it is not only a local rainfall line, a sufficient knowledge of the isotopic composition of local precipitation is not yet available.

Among the "autochthonous" streams, the Biela voda and Belá streams, dewatering the Vysoké Tatry Mts., have the highest proportions of the light isotopes. The presence of the light isotopes in the water of the Biely Váh, Dunajec and Poprad rivers is assumed. The increased representation of the light isotopes in the Váh River in the Kolárovo town is a consequence of the water of the Danube provenance entering into the Váh River through the Malý Dunaj water flow, eventually by a disguised transfer owing to groundwater infiltration from the Danube River. Isotopically the lightest water is proven in the Danube River in Bratislava, which corresponds to its Alpine origin. The distinct increase in the proportion of heavy isotopes in the Danube water in Komárno and Štúrovo towns is obviously a consequence of the increased share of the Váh and Hron rivers water in the sample (it was taken from the left bank), where apparently the water of flowing stream apparently modifies the strong Danube flow.

The specific isotopic composition was found in the water of Rudava and Malina flows. These left-side tributaries of the Morava River have up-to-now the highest documented presence of hydrogen and oxygen heavy isotopes, while the evaporation can be excluded. Both streams drain the western, windward slopes of the Malé Karpaty Mts. Despite no data about the distribution of isotopes in the precipitations in this area are available, their specific isotopic composition can be assumed. Such indications are in the higher representation of the oxygen and hydrogen heavy isotopes in the water of Vlára and Kysuca water flows.

5.6 Conclusions

The final part of the *Geochemical Atlas of Slovakia* is devoted to results of hydrogeochemical mapping of the surface water, being obtained in the frame of the project 04 08 *Geochemical Atlas of the Slovak Republic, part 7 – Surface Waters*. This project was solved in SGIDŠ within the years 2008–2014. The input data consisted of 10,960 samples of surface water, representing a sampling density one sample per 4.5 km^2. The sampling was not done in regular network, but it was modified to the density of river net in Slovakia. In the Atlas the following elements/compounds/indicators are evaluated: TDS, pH, Li, Na, K, NH_4, Mg, Ca, Sr, Mn, Fe, F, Cl, NO_3, SO_4, PO_4, HCO_3, Sb, As, Ba, Al, Cr, Cd, Cu, Pb, Se, Zn, SiO_2 and COD_{Mn}.

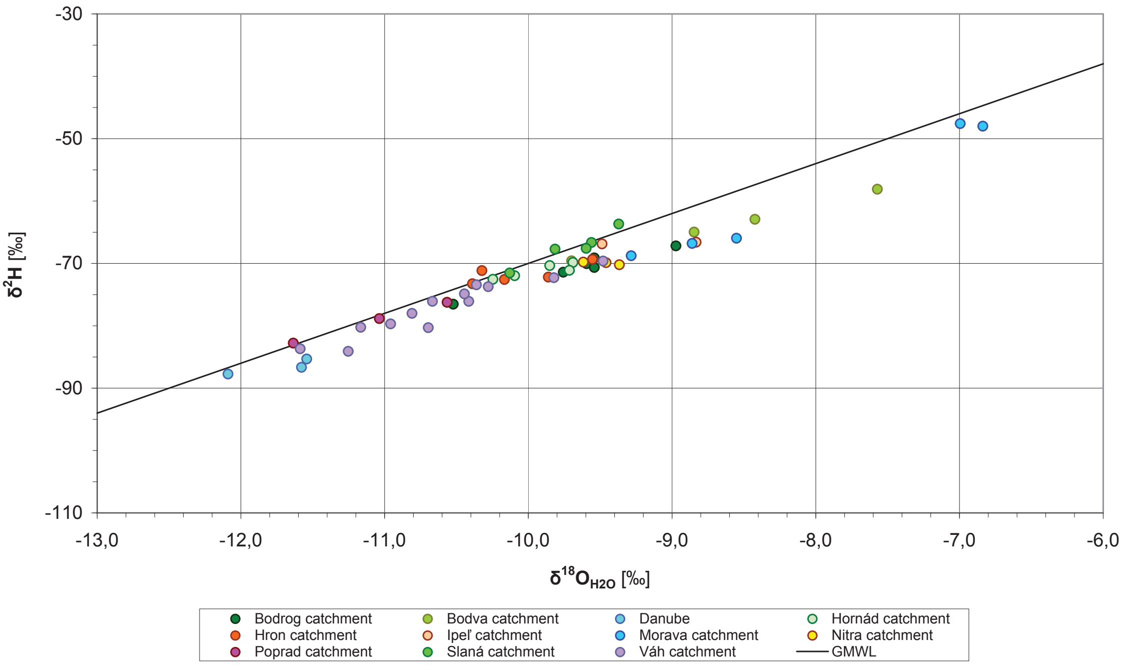

Fig. 5.22 Contents of $\delta^{18}O$ and $\delta^{2}H$ in Slovak rivers according to catchment areas.

The Geochemical Atlas of Surface Waters is focused mainly on clarification and interpretation of the distribution of elements/compounds/indicators in maps at a scale 1:1,000,000. For the first time in conditions of Slovakia, the genesis of elements/compounds in such important medium like the surface water was assessed.

The results of the geochemical mapping allowed to carry out hydrogeochemical assessment of the surface water. According to selected end members of the chemical composition of the surface water there were characterized the main chemical types of the water by means of ternary diagrams, statistical methods and thermodynamic analysis. Concerning the chemical composition, the surface water is characterized by the prevalence of Ca–HCO_3 compound. In cationic composition there prevails the calcium content and in variable representation in individual lithotypes present in the source environment there alternate the magnesium and calcium. In anionic composition there dominate the bicarbonates and the second most frequent compound represent sulphates. In individual groups in the varying proportions there is represented SiO_2.

According to the conceptual model the formation of the chemical composition of the surface water is very complex mechanism. Moreover, the surface flow is an open, dynamic system that is affected by a large number of factors. A simplified approach is based on the initial water - atmospheric precipitation (solid and liquid), which represents primary input for the formation of surface and groundwater. In this system it is clear that in the natural conditions of Slovakia the most important factor is the interaction of water – rock – gas. Therefore, the resulting chemical composition of surface water is the most dependent on the composition of the ground, altitude and climatic period. The chemical composition of surface water quickly reacts to climatic period (spring snow melt, torrential rainfall, etc.), which leads to significant changes in water quality.

In simple substantiation, surface water was divided into five groups, named A, B, C, D and E, which are characterized by petrography and geochemistry of catchment areas:

A) Acid alumosilicate rocks and siliciclastic sediments, as well as their metamorphic rock equivalents
B) Basic and intermediary rocks
C) Dominantly pelitic sediments
D) Dominantly siliciclastic rocks
E) Carbonate rocks

According to these groups the surface water was characterized hydrogeochemically in detail.

As an integral part of the atlas, also a comprehensive evaluation of the isotopic composition of the surface water is presented for the first time in the nation-wide Slovak scale. The isotopic composition of oxygen and deuterium, characterizing the water molecule, clearly points to their meteoric origin.

The formation of chemical composition of the surface water represents a complicated geochemical and biological system, where the most significant role in the Slovak conditions is played by the water–rock interaction and anthropogenic influence. The hydrobiological processes, influencing the chemical composition of the surface water, are not treated in this paper.

All data and interpretations constitute a basis for further evaluations especially of environmental and hydrological character. They are also important in terms of improving the status of natural waters in Slovakia. The results of the Geochemical Atlas of Surface Waters in connection with the results of monitoring of surface water quality, reflecting the temporal factor, represent a unique tool to fill the noble goal to improve water conditions in Slovakia and the whole continent.

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6. Mine Waters in the Slovak Part of the Western Carpathians – Distribution, Classification and Related Environmental Issues

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Abstract: The frequency of occurrence and amount of mine water in the country change in the longer term, depending on fluctuations in the intensity of mining activities and the availability of mineral deposits of interest to mining. Presented regional overview of the phenomenon in the Slovak part of the Western Carpathians depicts a situation which has changed significantly after 1990 due to the completion of ore deposits mining. Based on the collection of archive data and new field and laboratory measurements within 14 mining-deposit regions and 71 mining-deposit districts 1,041sources of mine water have been documented with a total discharge of 1.80 m^3 s^{-1}. Individual mine water resources and their characteristic discharge Q_{char} are divided into classes according to the hydrogeological type of deposit, Q_{char} value, the chemical composition of mine water and its quality in relation to the requirements for drinking water and water quality of surface streams. Of the said sum 0.381 $m^3 \cdot s^{-1}$ has confirmed and 0.448 $m^3 \cdot s^{-1}$ assumed suitability for drinking water preparation. The remaining amount with a poor quality represent potential sources of contamination of surface water. Overview of ongoing monitoring shows that persistent contamination of streams due to significant mine water discharges is a real environmental problem in many areas with abandoned mines presence, along with the risk of damage by sudden inrushes of mine water at the surface.

Key words: mine waters, mining hydrogeology, mining impacts, drinking water, surface water quality, Slovakia

6.1 Introduction

The territory of Slovakia is due to favourable hydrogeological and climatic conditions, famous for its abundant occurrences of mineral, thermal and natural waters. Thanks to rich history of mining, gradually – mostly since the Middle Ages – specific sources of water have appeared, as a consequence of drainage and accumulation effect of underground workings.

The Slovak historic mining was bound with mining centres in the Western Europe, mainly in Saxony and Austria. The birthplace of modern mining or at least recording of modern mining occurred during the 16th century in the Erzgebirge area of Germany. Methods of mining of the place, including dewatering and the environmental impacts associated with mining and mineral dressing are recorded in classic thesis *De Re Metallica* (Agricola, 1556). The peak of raw minerals extraction in Europe lasted from the end of the Middle Ages to the Early Modern Period. In Slovakia initially mainly gold, silver and copper were mined; in the last century iron had become a dominant mined metal. Production of iron ore reached its peak in the period 1911 – 1913 with an average annual extraction of 1.1 million tonnes (Stauch, 1938). After World War I in Slovakia developed mining of manganese and antimony, the production of precious metals was modernized and production of lead resumed. The youngest Slovak mining industry – coal and crude oil – developed as well. After a temporary decline, mining of magnesite increased, and the extraction of asbestos and gypsum was launched (Stauch, 1938). Last term of the recovery of mining and exploration activities in the period 1971 – 1985 was supported by government grants (Zámora, 2003). After the transition to a market economy after 1989, the State declared setback in ore mining programme and within a short time extraction at dozens of mines was terminated. All of them were abandoned after disposal of available equipment and safety measures at the mining works adit collars. Deep levels below the local erosion base have gradually filled-up by the water and on the surface have emerged new spontaneous outflows of mine water.

Deep mines drainage issues were initially dealt with by so-called mining experts, from the early 20th century by mining engineers. Only since 1955 hydrogeologists have begun to participate in solving them, particularly in the dewatering of extracted lignite/brown coal deposits and their relation to the significant sources of healing mineral waters. The hydrogeological service at the extraction of other types of minerals was rather an exemption in the mining plants. The first comprehensive survey on the occurrence of mine water in Slovakia, along with the hydrogeological characteristics of major deposits and common knowledge of the hydrogeology of mineral deposits, brought the third tome of Hydrogeology of Czechoslovak Socialist Republic (Homola & Klír, 1975). Later it was published a brief review of the occurrence and the possibilities of mine waters exploitation in Slovakia (Cicmanová et al., 1999), and their frequency, quantity, chemical composition and related environmental problems (Bajtoš, 2005).

In the years 2008 – 2011 SGIDŠ conducted regional hydrogeological research, the main objective of which was to collect, unite and analyse available data on mining waters in Slovakia and to develop a synthesis of knowledge about the quantities and formation of their chemical composition in relation to the deposit type and associated rocks drained by mining works (Bajtoš et al., 2011a). The purpose of the work was to ensure a missing comprehensive overview of sources of mine water in Slovakia in terms of their quantitative and qualitative parameters in respect of their practical use and the risk of negative impacts on the environment. This contribution presents the results of the research on the spatial distribution of mining waters in Slovakia, their hydrogeological classification, quantitative evaluation and classification of their chemical composition along with the evaluation of qualitative properties in relation to the requirements for drinking water quality. The paper discusses also the environmental problems associated with the occurrence of mine waters based on the actual results of the Monitoring of the impact of mining upon the environment at risk localities, implemented at SGIDŠ since 2007 (information is available at the website www.geology.sk), and results of the analysis of the potential risks generated by inrushes of mine water after completion of mining activities (Bajtoš et al., 2011b). Its aim is to document the present state of time-dependent occurrence of mine water resources, their negative impact on the environment and people's lives, eventually the beneficial uses, and at the same time to stimulate their further research.

6.2 Materials and methods

6.2.1 Input data

To characterize documented sources of mine water archival data are used amended on actual field measurements and laboratory analyses. The largest information archive base data are the final reports of regional hydrogeological research, hydrogeological surveys and deposit geological surveys of both search and detailed stages, stored in Geofond SGIDŠ, Bratislava. In our case the main source of data on one-off discharges of adit outflows were collected during fieldwork inventory at old mine workings (Záviš et al., 1996) situated outside the then mining fields. A large number of galleries with discharge was documented during the regional hydrogeological mapping of the Volovské vrchy Mts. in the basin of Hnilec (Malík et al., 1990), northern part of the Spiš-Gemer Ore Mts. (Scherer et al., 1999) and part of the Spiš-Gemer Ore Mts. in the Slaná River Catchment (Bajtoš, 2001). Sources of mine water in the Štiavnica-Hodruša ore field were documented in a detailed hydrogeological survey (Lukaj, et al., 1983) and then search for hydrogeological sources (Viest, et al., 1993). The assessment reflects the results of quantitative and qualitative regime observations of mining water sources, implemented in several hydrogeological surveys and studies of various mining-deposit areas. When collecting archive data it was necessary to individually evaluate the reliability and accuracy of laboratory analyses of mine water. The adopted analyses of the scope of a complete basic analysis (determined by the concentration of all macro-components) were checked by calculation ionic balance error. Those analyses were accepted with an error of less than 5%, in rare cases up to 10%. In the database of archive data have been collected 1,330 laboratory analyses with variable extent of the parameters determined.

The database of archive data was supplemented with actual field measurements of selected objects. The discharge of the effluent and basic physico-chemical water parameters were measured: temperature, specific electric conductivity (EC), water reaction (pH), and oxygen saturation. The discharge of outflow was measured according to local conditions by the volumetric method (using a container and stopwatch) or hydrometric wing A.OTT Kempten. On selected objects 120 water samples were taken for chemical analysis of water in the range: Na, K, Mg, Ca, Sr, NH_4, Mn, Fe, Fe^{II}, F, Cl, SO_4, NO_2, NO_3, PO_4, HCO_3, CO_3, SiO_2, Al, As, Ba, Cd, Cr, Cu, Hg, Pb, Sb, Se, Zn, Be, Ag, Ni, Co, B, Sn, V, Mo, aggressive CO_2 and COD_{Mn}. Of the 30 samples radiological indicators were determined: bulk activity of radon, bulk activity of radium 226 and uranium concentration. The above laboratory analyses of water were performed in an accredited laboratory GAL SGIDŠ in Spišská Nová Ves.

6.2.2 Ways of mine water sources classification

Documented sources of mine water in Slovakia have been categorized by place of occurrence, hydrogeological conditions of the deposit, the type of circulation of groundwater in the host rock environment, the amount of mine water, chemical type of mining water and its quality.

Regional classification rests in the on two levels definition of broad areas of occurrence of mining water. We distinguish mining-deposit regions and mining-deposit areas. The basis for the definition of mining-deposit regions is the spatial concentration of mining water sources occurrences within the boundaries of a particular region, corresponding to the regional geological division of Slovakia (Vass et al., 1988). Within mining-deposit regions mine water areas are delineated which correspond to the smaller territories areas or sites. In Slovakia, we have allocated 14 mining-deposit regions and 71 mining-deposit districts. They are listed in Table 6.2 and their spatial definition is shown in Fig. 6. 1.

Deposit-hydrogeological classification has been developed to indicate the source groups of mining water, which are characterized by an identical type of permeability of deposit rocks, similarities of circulation and draining of the groundwater by workings, common genesis type of chemical composition of mine waters and the similarity of their qualitative characteristics of water. It is based on a combination of definition of the basic deposit-hydrogeological types of deposit bodies and basic types of groundwater circulation in the host rock environment.

Delineation of basic hydrogeological types of deposit bodies is closely linked to the genetic breakdown of mineral deposits, because individual genetic types of deposits are developed at certain specific conditions in similar rocks and are characterized by an identical type of minerals associations. In Slovakia, we have allocated 18 hydrogeological types of deposits, whereas we relied on metallogenic division of Slovakia (Lexa et al., 2007). Their list, along with an overview of the number of occurrences of mining waters and basic quantitative indicators are given in Table 6.3, along with the basic types of groundwater circulation in the host rock environment.

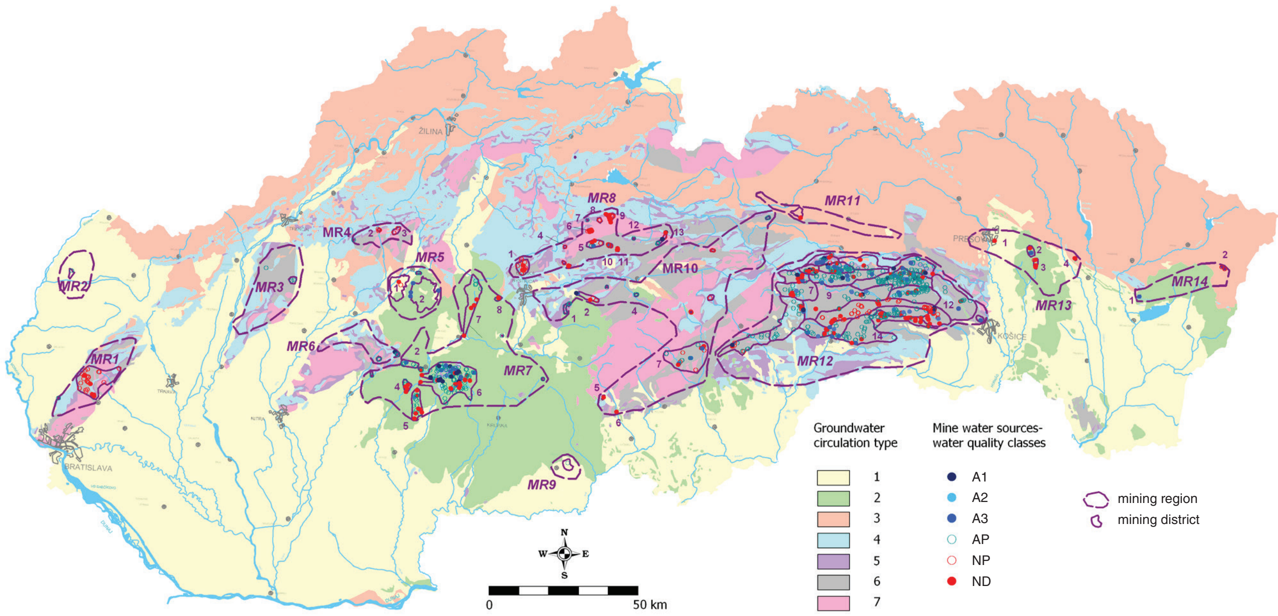

Fig. 6.1 Mining-deposit regions (MR) and mining-deposit districts (MD) of Slovakia with mine water occurrences.

6.2.3 Way of categorization of documented amounts of mine waters

Collected quantitative and qualitative data on documented sources of mine water have been used to categorize quantities of mine water, based on allocated deposit-hydrogeological types and regional data. This categorization takes into account the nature of the available groundwork material and the specific nature of resources evaluation. Documented quantities are categorized according to the value of the characteristic discharge Q_{char} of resources and also by the quality requirements for drinking water (Table 6.8). The categorization results give an overview of the amount of mine water suitable for drinking; they also indicate potential sources of contamination of surface waters, or groundwaters.

For the characteristic Q_{char} value we considered the arithmetic average of the available data set. The most aforementioned Q_{char} values – up to 938 from a total of 1,041 (90%) documented sources of mine water – is determined from single or repeated measurements.

In qualitative terms the documented sources of mine water are divided into classes according to suitability for treatment before being used for drinking purposes. The sources of mine water with the available laboratory analyses, we classified in categories A1, A2, A3 defined by Decree of the Ministry of the Environment 636/2004 Coll. as suitable for drinking purposes with varying intensity of treatment, or in the category of ND – water prohibited for drinking purposes. In the case of the absence of laboratory analyses the sources were assessed as likely complying with the class AP, and probably unsuitable in the class NP, individually by deposit hydrogeological type. For the assessment of the qualitative characteristics of the source of mine water there was available unconsolidated groundwork material, in particular as regards the scope of the determined indicators. The prevalence of cases there were available essential contents of ions, the extent of determined trace elements, however, was considerably variable and mainly data on the concentration of B, Se, Ag, and Sb were missing (Table 6.1).

Due to the uneven number of analyses available for the qualitative assessment of a particular source we derived for each quality indicator the so-called characteristic value. The method of calculating characteristic values depended upon the number n of available measurements of the relevant parameter in the reporting period:

provided $n \geq 24$: characteristic value corresponds to the value set of quality indicator with a probability 90% not exceeded (for dissolved oxygen with a exceeding probability 90%);

provided n = [11, 23): characteristic value is determined as the average of the three most unfavourable values of the set;

provided $n < 11$: characteristic value corresponds to the maximum value of the set.

Tab. 6.1 Number (n) and percentage (%) of objects with missing data on the content of individual water quality indicators established by laboratory analyses.

	Hg	**Sb**	**As**	**Ag**	**Ni**	**Se**	**B**	**Zn**	**Pb**	**Cd**	**Cr**	**Cu**	**Al**	**F**	**Ba**
n	14	40	4	67	54	42	126	9	5	10	11	5	30	23	53
%	5.2	15.0	1.5	25.1	20.2	15.7	47.2	3.4	1.9	3.7	4.1	1.9	11.2	8.6	19.8

Note: The total number of evaluated objects is 267

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6.3 Classification of Slovak mining waters

Documented sources of mine water in Slovakia have been qualified by geographical, deposit-hydrogeological, quantitative and qualitative hydrochemical criteria.

6.3.1 Regional distribution

Mining water sources are spatially spread very unevenly, concentrated mainly in the historic mining district in the central part of Slovakia. Among allocated 14 mining-deposit regions (MR) Gemer zone (MR 12) in eastern Slovakia is the largest and richest in mine water occurrences, divided into 20 mining-deposit districts (MD). Boundaries of these districts are determined on the basis of general map of the Spiš-Gemer Ore Mts. and their names correspond to the occurrences of metamorphic-hydrothermal vein mineralisation (metamorphic-hydrothermal vein mineralisation) by monograph Grecula et al. (1995), which contains a detailed description of the geology of deposits and their ore minerals and quality, as well as history of exploration and mining. Among them Slovinky – Gelnica (MD 10) is the most important district in terms of mine waters occurrences and their quantity. Another important region is Central Slovakia Neovolcanites Field (MR7), where among 10 MD extremely important is Štiavnica-Hodruša ore district (MD 7 – 6). Thanks to the size and amount of mine water reserves of coal in the Upper Nitra (MR 5) are significant along with South-Slovakia Lowland (MR 2). The remaining MRs are relatively poor in the incidence of mine water.

6.3.2 Classification of sources of mine water according the basic hydrogeological types of deposit bodies

Nature of the circulation, regime and formation of the chemical composition of water in the reach of worked deposits depends primarily on the geological structure of deposits and on the type and mineral composition of deposit bodies, also on the elevation position deposit against the local erosion base level, geometry of mine workings, drainage rate of hydrogeological collectors and precipitation-climatic conditions of the territory. Whereas individual genetic types of deposits are developed under certain specific conditions in similar rocks and are characterized by an identical type of mineral associations, the basic hydrogeological types of the deposit bodies occurring in the territory of Slovakia can be derived from the genetic breakdown of mineral deposits (Lexa et al., 2007). The basic hydrogeological types include those types of deposits which have or had previously been mined and therefore they host the mine water. Of the 31 types of deposits (or mineralisation types) of this genetic division of deposits we derived 18 basic deposit-hydrogeological types:

1) Sn, W and Mo greisen pneumatolithic-hydrothermal and hydrothermal mineralisation (*phm*)
   Deposits of neo-Hercynian late- to post-orogene stage of this type represent a hydrothermally altered peripheral parts of the granitic bodies of irregular shape. They have a fissure permeability and are component of the hydrogeological massif of intrusive magmatic rocks, and their permeability is similar to encompassing rocks. Therefore, the groundwater has silicatogenic dissolved solids.
2) syngenetic massive-sulphidic pyrite-pyrrhotite mineralisation (*ssu*)
   Stratiform sulphides horizons originated in palaeo-Hercynian metallogenic stage. They are lenticular-shaped bodies with fissure permeability type whose class is not significantly different from the degree of permeability of host metamorphic Palaeozoic hydrogeological massif. Their groundwaters have sulphidogenic dissolved solids – metallosulphate acid waters are formed.
3) uranium-molybdene-copper mineralisation – syngenetic/diagenetic, infiltration or vein-stockwork-impregnation (*u*)
   This type of neo-Hercynian or even palaeo-Alpine mineralisation consists of irregularly shaped bodies tied to specific layer sequences and tectonic zones. Their fissure permeability is equivalent to permeability of Palaeozoic host rocks. Oxidation of sulphides at varying rates takes place in deposit bodies, along with dissolution of carbonates and hydrolysis of silicate minerals.
4) vein and stockwork-impregnation gold-scheelite-arsenopyrite mineralisation (*sche*)
5) gold-antimonite vein and stockwork-impregnation mineralisation (*az*)
6) siderite-sulphidic vein and stockwork-impregnation mineralisation (*sz*)
7) copper vein and stockwork-impregnation mineralisation (*mz*)
   Deposits of the type *sche* and *sz* belong to palaeo-Alpine to late-orogenic hydrothermal vein mineralisation. True hydrothermal veins reach small thicknesses (generally less than 5 m, maximum 20 m); they are usually situated in steeply inclined pre-Mesozoic host rocks and they are tectonically segmented. They are accompanied by stockworks and impregnation zones. They have fissure permeability which does not significantly differ from the permeability class of the host rock. From hydrogeochemical point of view it is a very variable environment with varying proportions of quartz, carbonate and sulphide minerals. Therefore, sulphidogenic, carbonatogenic and silicatogenic dissolved solids are present in various proportions.
8) siderite-ankerite metasomatic mineralisation (*sid*)
9) magnesite metasomatic mineralisation (*mag*)
10) talc metasomatic mineralisation (*mst*)
   The geometries of the deposit bodies of the types *mag*, *sid* and *mst* are very similar, since they represent metasomatically (palaeo-Alpine orogeny stage) altered bodies of synsedimentary carbonates deposited within Palaeozoic metamorphic sediments. Their original form is heavily modified by tectonic processes. Groundwater in these deposits is enriched in the carbonatogenic dissolved solids, and depending on

Tab. 6.2 Documented quantity Q_Σ in $l \cdot s^{-1}$ of mine water outflows in mining regions (MR) and mining districts (MD)

MD number	Mining district (MD)	n	Q_Σ	Frequency of present HG types *n*	Summary yield Q_Σ ($l \cdot s^{-1}$) of present HG types
MR 1 Malé Karpaty Mts.		**33**	50.67	**13 ssu, 13 az, 4 az/ssu, 3 mn**	**31.07 ssu, 11.41 az, 6.9 az/ssu, 1.29 mn**
1-1	Stupava	3	1.29	3 mn	1.29 mn
1-2	Pezinok - Pernek	30	49.38	13 az, 4 az/ssu, 13 ssu	11.41 az, 6.9 az/ssu, 31.07 ssu
MR 2 Záhorská nížina Lowland		**1**	25	**1 uh**	**25 uh**
2-1	Gbely-Kúty	1	25	1 uh	25 uh
MR 3 Považský Inovec Mts.		**2**	6	**2 zlt**	**6 zlt**
3-1	Zlatníky	2	6	2 zlt	6 zlt
MR4 Strážovské vrchy Mts.		**6**	0.82	**5 az, 1 sz**	**0.72 az, 0.1 sz**
4-1	Čierna Lehota - Vtáčnik	1	0.1	1 sz	0.1 sz
4-2	Čavoj	3	0.42	3 az	0.42 az
4-3	Chvojnica	2	0.3	2 az	0.3 az
MR 5 Upper Nitra Basin		**8**	333.7	**6 uh, 2 z**	**333.7 uh, 0.15 z**
5-1	Nováky	2	114	2 uh	114 uh
5-2	Handlová - Cigeľ	4	219.7	4 uh	219.7 uh
5-3	Kopanice	2	0.15	2 z	0.15 z
MR 6 Tríbeč Mts.		**7**	10.92	**4 z, 3 sz**	**9.82 z, 1.1 sz**
6-1	Jedľové Kostoľany	3	1.1	3 sz	1.1 sz
6-2	Veľké Pole - Píla	4	9.82	4 z	9.82 z
MR 7 Central Slovakia Neovolcanic Field		**190**	460.94	**185 z, 3 i, 2 uh**	**455.39 z, 2.35 i, 3.2 uh**
7-1	Obyce - Včeláre	1	3	1 uh	3 uh
7-2	Horné Hámre	7	2.6	7 z	2.6 z
7-3	Žarnovica (Kožený vrch)	8	0.53	8 z	0.53 z
7-4	Nová Baňa	8	1.86	8 z	1.86 z
7-5	Rudno-Pukanec	20	24.95	20 z	24.95 z
7-6	Štiavnicko-hodrušský rudný obvod	131	341.45	131 z	341.45 z
7-7	Kremnica	9	83.75	9 z	83.75 z
7-8	Malachov	3	2.35	3 z	2.35 z
7-9	Turová	1	0.2	1 uh	0.2 uh
7-10	Slatinské Lazy, Kalinka	2	0.25	2 z	0.25 z
MR 8 Nízke Tatry Mts.		**74**	129.29	**47 az, 14 mz, 6 sz, 5 sche, 2 phm**	**42.31 az, 39.72 sche, 15.54 mz, 1.32 sz, 0.4 phm**
8-1	Špania Dolina, Staré Hory	14	15.54	14 mz	15.54 mz
8-2	Hiadeľ	1	1	1 az	1 az
8-3	Medzibrod	5	2.78	5 az	2.78 az
8-4	Korytnica - Pustá dolina	1	0.1	1 az	0.1 az
8-5	Jasenie (-Soviansko, Lomnistá)	5	39.72	5 sche	39.72 sche
8-6	Magurka	11	13.45	11 az	13.45 az
8-7	Partizánska Ľupča	2	0.4	2 phm	0.4 phm
8-8	Rišianka	3	0.6	3 az	0.6 az
8-9	Dúbrava	11	45.42	11 az	45.42 az
8-10	Dolná Lehota (Dve vody)	7	3.78	7 az	3.78 az
8-11	Lom	6	4.94	6 az	4.94 az
8-12	Trangoška	1	0.2	1 sz	0.2 sz

MD number	Mining district (MD)	n	Q_{Σ}	Frequency of present HG types *n*	Summary yield Q_{Σ} ($l \cdot s^{-1}$) of present HG types
8-13	Nižná Boca	7	1.36	5 sz, 2 az	1.12 sz, 0.24 az
MR 9 Juhoslovenská nížina Lowland		1	75	1 uh	75 uh
9-1	Veľký Krtíš	1	75	1 uh	75 uh
MR 10 Vepor Zone		**42**	17.72	**12 mst, 9 lim, 6 az, 5 ssu, 3 mz, 3 sz, 2 mg, 2 u**	**10.36 mst, 2.95 lim, 1.54 az, 0.98 mz, 0.7 sz, 0.68 ssu, 0.48 mag, 0.03 u**
10-1	Poniky	6	1.75	6 lim	1.75 lim
10-2	Ľubietová	6	2.18	3 lim, 3 mz,	1.2 lim. 0.98 mz
10-3	Osrblie	1	0.5	1 sz	0.5 sz
10-4	Čierny Balog	2	0.2	2 sz	0.2 sz
10-5	Ružiná	1	0.43	1 mag	0.43 mag
10-6	Podrečany	1	0.05	1 mag	0.05 mag
10-7	Hnúšťa-Kokava	17	11.4	12 mst, 4 az, 1 ssu	10.36 mst. 0.94 az. 0.1 ssu
10-8	Tisovec-Magnetový vrch	3	0.9	2 az, 1 ssu	0.6 az. 0.3 ssu
10-9	Muráň - Hrdzavá dolina	1	0.1	1 ssu	0.1 ssu
10-10	Heľpa	2	0.18	2 ssu	0.18 ssu
10-11	Kravany-Sp.Bystré	2	0.03	2 u	0.03 u
MR 11 Popradská a Hornádska kotlina		2	8.16	2 mn	8,16 mn
11-1	Kišovce-Švábovce	2	8.16	2 mn	8.16 mn
MR 12 Gemer Zone		**656**	662.73	**535 sz, 68 az, 13 u/sz, 10 sid, 10 u, 7 mag, 4 sz/sid, 4 ssu, 2 phm, 1 ssu/sz, 1 sz/sa, 1 sa**	**455.72 sz, 56.96 az, 31.59 u/sz, 21.48 sid, 20.1 u, 18.15 mag, 17.75 phm, 16.37 ssu, 11.43 sz/sa, 10.0 sa, 2.38 sz/sid, 0.44 ssu/sz,**
12-1	Novoveská Huta - Hanisková	23	60.54	13 u/sz, 9 u, 1 sa	31.59 u/sz, 18.95 u, 10 sa
12-2	Dobšiná	23	24.16	23 sz	24.16 sz
12-3	Mlynky - Biele Vody	13	6.32	10 sz, 3 sz/sid	4.24 sz, 2.08 sz/sid
12-4	Gretľa - Ráztoky - Bindt	47	55.27	46 sz, 1 sz/sa	43.84 sz, 11.43 sz/sa
12-5	Rudňany - Poráč - Matejovce	6	32.75	6 sz	32.75 sz
12-6	Krompachy - Žakarovce - Jaklovce	27	33.32	27 sz	33.32 sz
12-7	Rejdová - Vyšná Slaná - Vlachovo	18	9.95	18 sz	9.95 sz
12-8	Hnilec - Čierna Hora - Nálepkovo	44	56.72	42 sz, 2 phm	38.97 sz, 17.75 phm
12-9	Henclová - Stará voda - Švedlár - Mníšek	21	10.29	21 sz	10.29 sz
12-10	Slovinky - Gelnica	141	123.35	141 sz	123.35 sz
12-11	Mníšek - Prakovce - Perlová dolina - Kojšov	52	26.75	52 sz, 1 ssu	25.23 sz, 1.52 ssu
12-12	Margecany - Opátka - Košická Belá - Košice	13	5.45	13 sz	5.45 sz
12-13	Turecká - Rožňava - Rákoš	25	32.47	25 sz	32.47 sz
12-14	Krásnohorské Podhradie - Drnava - Úhorná	23	12.81	23 sz	12.81 sz
12-15	Smolnícka Huta - Jedľovec - Humel - Trochanka	27	35.2	27 sz	35.2 sz
12-16	Štós - Medzev - Poproč	45	31.24	41 sz, 3 ssu, 1 ssu/sz	15.95 sz, 14.85 ssu, 0.44 ssu/sz
12-17	Brdárka - Kobeliarovo - Ochtiná - Čierna Lehota	21	22.72	14 sz, 5 sid, 1 sz/sid, 1 u	14.68 sid, 6.59 sz, 1.15 u, 0.3 sz/sid
12-18	Čučma - Bystrý potok - Poproč - Zlatá Idka	68	56.96	68 az	56.96 az
12-19	Jelšava - Lubeník- Sirk	17	20.1	mag 6, sz 6, sid 5	12.15 mag, 6.8 sid, 1.15 sz
12-20	Košice Bankov	1	6.0	1 mag	6.0 mag
MR 13 Šariš Region		**13**	13.56	**8 i, 4 z, 1 sol**	**7.18 i, 6.37 z, 0.01 sol**

MD number	Mining district (MD)	n	Q_Σ	Frequency of present HG types *n*	Summary yield Q_Σ ($l \cdot s^{-1}$) of present HG types
13-1	Prešov Solivar	1	0.01	1 sol	0.01 sol
13-2	Zlatá Baňa	4	6.37	4 z	6.37 z
13-3	Dubník	6	4.98	6 i	4.98 i
13-4	Merník	2	2.2	2 i	2.2 i
MR 14 Vihorlatské vrchy Mts.		**4**	2.15	**3 i, 1 lim**	**2.1 i, 0.05 lim**
14-1	Trnava pri Laborci	1	0.05	1 lim	0.05 lim
14-2	Ladomírov	3	2.1	3 i	2.1 i

Explanations: Hydrogeological types of deposits codes according Table 6. 3.

the type of ore mineralisation karst process is present. This is particularly valid for magnesite deposits, in which we can anticipate karst-fissure type of permeability. The deposits of talc and siderite are without significant manifestation of karstification.

11) syngenetic deposits of gypsum and anhydrite (*sa*)
These are fairly large synsedimentary anhydrite bodies that underwent hydration on the periphery and inside the bodies and along fracture zones and faults, resulting in gypsum formation. They have a fissure-karst permeability type and are often accompanied by collector layers of rauhwackes, dolomite or limestone. Sulphatogenic dissolved solids composition in groundwater is typical for them.

12) manganese sedimentary-diagenetic mineralisation (*mn*)
Deposits are formed by thin layers in sediments with fissure permeability type. Therefore, their impact on the overall deposit-hydrogeological conditions is relatively small and is dominated by the influence of accompanying rocks.

13) precious metal and polymetallic vein-stockwork and polymetallic veinlet-impregnation mineralisation (*z*)
This group involves intersecting true hydrothermal veins and irregular bodies of veinlet-impregnation mineralisation of neo-Alpine orogenic stage. Steeply inclined veins have a large depth range. Their permeability may differ significantly depending upon the neovolcanic host rocks permeability and therefore they can act either as a hydraulically substantially conductive structure or as a hydraulic barrier. Groundwater has silicatogenic dissolved solids and variable contribution of sulphidogenic and carbonatogenic dissolved solids.

14) mercury and opal stockwork-impregnation mineralisation (*i*)
Small bodies of stockwork-impregnation mineralisation of neo-Alpine orogenic stage are irregularly shaped. The degree and nature of permeability is not different from neovolcanic host rocks. Mine water is dominated by silicatogenic and sulphidogenic dissolved solids.

15) goethite-limonite mineralisation of cold springs and highly-sulphidation epithermal mineralisation (*lim*)
Small bodies of goethite and limonite of neo-Alpine orogenic stage in the near-surface zone of neovolcanites or different types of hydrogeological massif.

16) coal, lignite (*uh*)
Subhorizontally deposited layers of coal are part of the Neogene filling of intramountain depressions and are usually developed with large areal extent. They have low permeability of the fissure type. The presence of sulphides in them causes the increase of the share component of sulphidogenic dissolved solids in groundwater. Mine water of those deposits comes from overlying or underlying aquifers.

17) halite (*sol*)
Under the presence of water intensive leaching and formation of underground cavities occur in synsedimentary layers of halite. In this case, the permeability is of the karst type and the water attains halogenic dissolved solids in water – with resulting formation of brine.

18) gold placers
They are located in Quaternary sediments with intergranular permeability. Within the deluvial sediments on the metamorphic rock masses they are considered to create the near-surface zone of hydrogeological massif.

Individual hydrogeological types of deposit are usually formed in the typical environment of the host rocks. This applies to synsedimentary deposits, but also to younger deposit structures linked to tectonic predisposition and geochemical barriers. For the purposes of this assessment basic types of host rock deposits can be defined according to the type of groundwater circulation. These reflect the fundamental differences between different types of hydrogeological collectors, regarding the essential features of their geometry, the type and degree of their permeability and their type of hydraulic regime. We distinguish 7 types of host rocks: 1) hydrogeological massif of magmatic rocks, 2) hydrogeological massif of Palaeozoic metamorphites, 3) hydrogeological massif of non-karst Mesozoic, 4) karst Mesozoic, 5) hydrogeological massif of Palaeogene sediments, 6) stratovolcanic type, 7) basinal type. The usual types of the groundwater circulation in certain hydrogeological deposit type, along with the number and yield of the documented sources of mine water are given in Table 6.3.

Tab. 6.3 Classification documented sources of mine water by hydro-type deposit bodies

	Type code	Type of deposit	Type of groundwater circulation	n	Q_{Σ} l·s^{-1}	$Q_{Ø}$ l·s^{-1}	Q_{min} l·s^{-1}	Q_{max} l·s^{-1}
1	phm	greisen (Sn, W) and molybdene pneumatolithic-hydrothermal to hydrothermal mineralisation	hydrogeological massif of Palaeozoic metamorphites a	4	18.15	4.54	0.20	15.11
2	ssu	syngenetic massive-sulphidic pyrite-pyrrhotite mineralisation	hydrogeological massif of Palaeozoic metamorphites	27	55.46	2.05	0.03	11.89
3	u	uranium-molybdene-copper mineralisation (syngenetic/ diagenetic, infiltration or vein-stockwork-impregnation)	hydrogeological massif of Palaeozoic metamorphites	26	54.72	2.11	0.01	15.0
4	sche	vein and stockwork-impregnation gold-scheelite-arsenopyrite mineralisation	hydrogeological massif of magmatic rocks	5	39.72	7.94	0.31	17.24
5	az	gold-stibnite vein and stockwork-impregnation mineralisation	hydrogeological massif of magmatic rocks, hydrogeological massif of Palaeozoic metamorphites	139	142.94	1.03	0.01	15.04
6	sz	siderite-sulphidic vein and stockwork-impregnation mineralisation	hydrogeological massif of Palaeozoic metamorphites	554	472.85	0.85	0.01	26.42
7	mz	copper vein and stockwork-impregnation mineralisation	hydrogeological massif of Palaeozoic metamorphites	17	16.52	0.97	0.03	5.45
8	sid	siderite-ankerite metasomatic mineralisation	hydrogeological massif of Palaeozoic metamorphites	10	21.48	2.15	0.05	10.0
9	mag	magnesite metasomatic mineralisation	hydrogeological massif of Palaeozoic metamorphites	9	18.63	2.07	0.05	10.0
10	mst	talc metasomatic mineralisation	hydrogeological massif of magmatic rocks	12	10.36	0.86	0.18	2.67
11	sa	syngenetic deposit of gypsum and anhydrite	hydrogeological massif of non-karst Mesozoic	1	10.0	10.0	10.0	10.0
12	mn	manganese sedimentary-diagenetic mineralisation	hydrogeological massif of non-carbonate Mesozoic or Palaeogene sediments	5	9.45	1.89	0.19	4.77
13	z	precious-metal and polymetallic vein and stockwork-impregnation mineralisation	stratovolcanic type	195	471.73	2.42	0.01	252
14	i	mercury and opal stockwork-impregnation mineralisation	stratovolcanic type, hydrogeological massif of Palaeogene sediments	14	11.63	0.83	0.05	2.0
15	lim	goethite-limonite mineralisation of cold springs	stratovolcanic type, hydrogeological massif of magmatic rocks or of Palaeozoic sediments	10	3.00	0.30	0.05	1.0
16	uh	coal, lignite	basinal type	10	436.9	43.69	0.20	112
17	sol	halite	basinal type	1	0.01	0.01	0.01	0.01
18	zlt	gold placers	hydrogeological massif of magmatic rocks	2	6	3.0	2.0	4.0

6.3.3 Classification of resources by mining water discharge

In quantitative terms, we register the documented source of mine water in 5 classes, according to the characteristic yield Q_{char} (Table 6.4). The second class outnumbers the others at an interval of values Q_{char} = 0.1 – 1 l·s^{-1}. The most significant in terms of the total amount documented is, however, the fourth class, where 24 sources with a yield in the range from 10 – 100 l·s^{-1} give a summary discharge of 552 l·s^{-1}. The biggest of them are: Hlavná dedičná štôlňa (Main Heritage Gallery; Fig. 6. 2) dewatering Kremnica ore district (MD 7-7, Q_{char} = 75 l·s^{-1} – without the amount of surface water conveyed into the mine to drive an underground hydroelectric power plant), two drainage pits at the coal deposit Nováky (5-1 MD, totally 115 l·s^{-1}), the main gallery of the coal seam in Cigeľ (MD 5-2, Q_{char} = 68 l·s^{-1}), Baňa Dolina in Veľký Krtíš (MD 9-1, 75 l·s^{-1}). To the class V belong Voznická Drainage Gallery, which drains Štiavnica-Hodruša ore district (MD 7-6, Q_{char} = 252 l·s^{-1}) and Stará štôlňa (Old Gallery) at Handlová coal deposit (MD = 5-2, Q_{char} = 112 l·s^{-1}).

6.3.4 Classification of mine water sources by chemical composition

In terms of total dissolved solids (TDS content) the mine waters are classified by Alekin's classification used for fresh groundwater (Table 6.5). The most frequent is the moderate mineralisation in the range of 200 to 500 mg.l^{-1}

Fig. 6.2 Mouth of Main Heritage Gallery of Emperor Ferdinand near Žiar nad Hronom, draining Kremnica ore district

ter rises in designated classes from CH^{I} to CH^{VI} with the transition of chemical species from distinct through indistinct and intermediary to mixed types.

Qualitative characteristics of mine waters are evaluated according to current legal standards and the results of this assessment are set out below.

6.4 Categorisation of mine water quantities according to the quality requirements for drinking water

The quantity of mining waters bound to various hydrogeological types of deposits, documented in Slovakia in mining-deposit regions and districts, we have divided by quality classes. As described in the methodological part of this text, we have categorized different sources of mine water according to the requirements for drinking water pursuant to Decree of the Ministry of the Environment 636/2004 Coll. We have carried out the categorisation in the range of selected physical and chemical indicators of quality that reflect well the risk from natural geochemical conditions at sites. There are not evaluated microbiological and biological indicators or organic indicators that reflect the current state of exploited deposits or anthropogenic load of the site and in the long run may be highly variable. Generally it can be assumed that in the case of microbiological and biological indicators a risk of occasional presence exists, which necessitates the installation and operation of a disinfection facility. In the case of organic indicators we assume in abandoned mining works mostly very low risk of exceeding the limit for drinking water, as confirmed by laboratory analyses available from some mining water sources. The levels of radiological indicators in mining waters according to available studies meet the requirements for drinking water. This is valid even for the mine water of U – Mo – Cu mineralisation (s), occurring dominantly in Novoveská Huta area (MD 12-1); at the time of extraction the mine water was characterized by a high level of radiation. The high content of radon is documented only in mining water of stibnite veins (*az*) and greisen Sn-W mineralisation (*phm*), flowing out from galleries in Gemeride granites (MD 12-18, or MD 12-8).

The breakdown of the quantities of mine water documented by the quantity (as defined in Table 6.4) and the quality classes are shown in Table 6.7 and in Figs. 6. 3 and 6. 4. Of the total amount of documented Q_{AN} = 1,799.55 l·s^{-1} in the recorded sources of mine water corresponds qualitatively suitable Q_A proportion 829.53 l·s^{-1} (46%) of mining water. Most of the quantity Q_A (54% Q_A) was assigned to the quality class AP by analogy – for lack of laboratory analyses. The amount 970.02 l·s^{-1} (66.9%) is considered unsuitable for water quality purposes; the predominant proportion of the amount (82%) is documented by laboratory analyses. These resources are mostly the

Tab. 6.4 Discrimination of quantitative classes of mining water resources

Class	Discharge class	***Q*** l·s^{-1}	n	Q_{Σ} l·s^{-1}	RL_A mg·l^{-1}
I	very low,	< 0.1	231	10.66	88
II	low	0.1 – 1	574	210.06	87
III	moderate	1 – 10	209	551.77	312
IV	high	10 – 100	24	662.96	731
V	very high	>= 100	2	364.00	1048

Explanation: Q_{Σ} - the sum of the yield characteristic Q_{char} of objects pertaining to the quantitative class; RL_A - the arithmetic mean of the characteristic values of total dissolved solids (TDS content) in the relevant quantitative class.

Tab. 6.5 Classification of sampled mine water sources by the total dissolved solids

Class	Dissolved solids class	Dissolved solids values range mg·l^{-1}	n	DS_A mg·l^{-1}	Prevailing macrochemical class
S^{I}	very low,	< 100	19	78	CH^{IV}
S^{II}	low	100 – 200	68	149	CH^{II}, CH^{I}
S^{III}	moderate	200 – 500	120	323	CH^{I}, CH^{II}
S^{IV}	high	500 – 1,000	57	712	CH^{I}, CH^{IV}, CH^{II}
S^{V}	very high	>= 1,000	30	2,137	CH^{IV}, CH^{V}

In terms of the macrochemical composition of mine water we distinguish 7 basic groups of chemical types. Their overview along with a large representation of sampled objects is presented in Table 6.6. The allocated groups according the type of chemical composition document the fact that the variability in macrochemical composition of mine water is mainly determined by the ratio among the four basic components – calcium, magnesium, bicarbonate anion and sulphate anion. Only in rare cases aluminium or iron have a high proportion of TDS. The mean TDS of wa-

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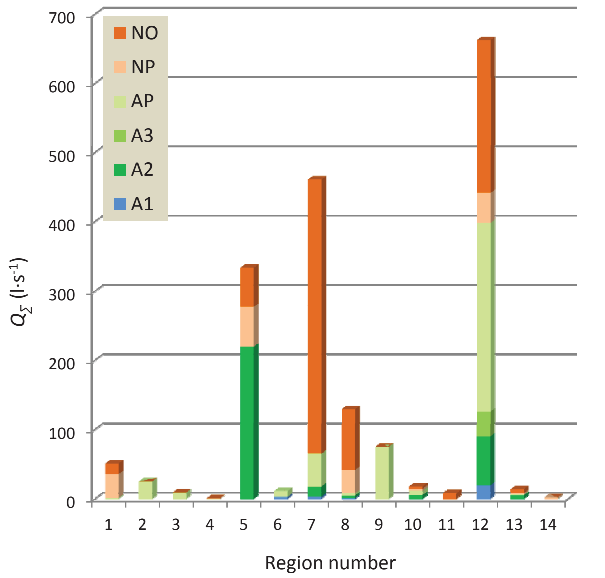

Fig. 6.3 Amounts of mine water of mining deposit regions divided in quality classes. Region labels are conform to Tab.6.3.

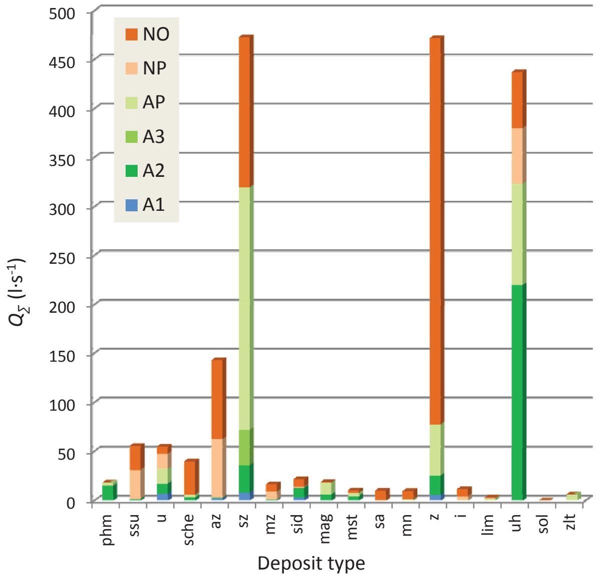

Fig. 6.4 Amounts of mine water of hydrogeological deposit types divided in quality classes. Codes of deposit types are stated in Tab.6.4.

Tab. 6.6 Allocation of classes by macrochemical mine water composition

Class	Chemical type according prevailing ions	Gazda's chemical type	*n*	RL_A mg·l^{-1}
CH^{I}	Ca-Mg-HCO_3	A_2 distinct	90	376
CH^{II}	Ca-Mg-HCO_3	A_2 indistinct	82	414
CH^{III}	Ca-Mg-SO_4-HCO_3	A_2-$S_2(SO_4)$ intermediary, A_2-$S_2(SO_4)$ mixed, A_2 intermediary, A_2 mixed	30	439
CH^{IV}	Ca-Mg-SO_4	$S_2(SO_4)$ indistinct and intermediary	48	638
CH^{V}	Ca-Mg-SO_4	$S_2(SO_4)$ distinct	32	984
CH^{VI}	Al(Fe)-Ca-SO_4	$S_3(SO_4)$ distinct and indistinct, $S_2(SO_4)$-$S_3(SO_4)$ intermediary	6	658
CH^{VII}	Na-Cl	S_1(Cl) distinct	1	5,000

potential sources of contamination. In terms of summary discharge of evaluated sources the class IV is the most represented (sources with Q_{char} = 10 – 100 l·s^{-1}) with the class yield of Q_{AN}^{IV} = 663 l·s^{-1} (37% of the total discharge Q_{AN}). Of the total number of documented sources of mine water n_{AN} = 1041 the majority (55%) belongs to the class Q^{II} (Table 6.8).

Tab. 6.7 Quantities of mine waters in documented sources according to quantity and quality classes

Q = l·s^{-1}		Quality classes of mine waters						
		A1	**A2**	**A3**	**AP**	**NP**	**ND**	**AN**
Quantity classes	**I**	Q_{A1}^{I} = 0.22	Q_{A2}^{I} = 0.25	Q_{A3}^{I} = 0.31	Q_{AP}^{I} = 8.39	Q_{NP}^{I} = 0.81	Q_{ND}^{I} = 0.68	$\mathbf{Q_{AN}^{I} = 10.66}$
	II	Q_{A1}^{II} = 6.63	Q_{A2}^{II} = 12.41	Q_{A3}^{II} = 2.54	Q_{AP}^{II} = 118.21	Q_{NP}^{II} = 30.39	Q_{ND}^{II} = 39.88	$\mathbf{Q_{AN}^{II} = 210.01}$
	III	Q_{A1}^{III} = 18.94	Q_{A2}^{III} = 61.43	Q_{A3}^{III} = 33.54	Q_{AP}^{III} = 200.75	Q_{NP}^{III} = 61.55	Q_{ND}^{III} = 175.56	$\mathbf{Q_{AN}^{III} = 551.77}$
	IV	Q_{A1}^{IV} = 0	Q_{A2}^{IV} = 25.11	Q_{A3}^{IV} = 0	Q_{AP}^{IV} = 228.7	Q_{NP}^{IV} = 83.0	Q_{ND}^{IV} = 326.15	$\mathbf{Q_{AN}^{IV} = 662.96}$
	V	Q_{A1}^{V} = 0	Q_{A2}^{V} = 0	Q_{A3}^{V} = 0	Q_{AP}^{V} = 0	Q_{NP}^{V} = 0	Q_{ND}^{V} = 364.0	$\mathbf{Q_{AN}^{V} = 364.0}$
In total		Q_{A1} = 25.79	Q_{A2} = 318.9	Q_{A3} = 36.39	Q_{AP} = 448.35	Q_{NP} = 175.75	Q_{ND} = 794.27	$\mathbf{Q_{AN} = 1,799.45}$
		Q_A = 829.43				Q_N = 970.02		

Explanations: I-V – classes of characteristic yield mine water sources (according to the criteria set out in Table 6.4); A3, A2, A1 – category of water quality according to the Ministry of Environment Decree No. 636/2004 Coll. verified by laboratory analyses; AP, NP - quality categories determined by the analogy for objects with missing laboratory testing; ND – water not meeting the requirements of the Decree of the Ministry of the Environment 636/2004 Coll.; *Q* – summary of the amount of mine water resources assigned to a certain class of quantity (^{superscript}) and quality ($_{subscript}$).

Tab. 6.8 Frequency of documented sources of mine water by quantitative and qualitative classes

n		Quality classes of mine waters						
		A1	**A2**	**A3**	**AP**	**NP**	**ND**	**AN**
Quantity classes	**I**	$n_{A1}^{I} = 5$	$n_{A2}^{I} = 4$	$n_{A3}^{I} = 5$	$n_{AP}^{I} = 179$	$n_{NP}^{I} = 21$	$n_{ND}^{I} = 17$	$\boldsymbol{n_{AN}^{I} = 231}$
	II	$n_{A1}^{II} = 20$	$n_{A2}^{II} = 31$	$n_{A3}^{II} = 6$	$n_{AP}^{II} = 353$	$n_{NP}^{II} = 94$	$n_{ND}^{II} = 70$	$\boldsymbol{n_{AN}^{II} = 574}$
	III	$n_{A1}^{III} = 6$	$n_{A2}^{III} = 21$	$n_{A3}^{III} = 8$	$n_{AP}^{III} = 84$	$n_{NP}^{III} = 27$	$n_{ND}^{III} = 63$	$\boldsymbol{n_{AN}^{III} = 209}$
	IV	$n_{A1}^{IV} = 0$	$n_{A2}^{IV} = 4$	$n_{A3}^{IV} = 0$	$n_{AP}^{IV} = 4$	$n_{NP}^{IV} = 3$	$n_{ND}^{IV} = 13$	$\boldsymbol{n_{AN}^{IV} = 24}$
	V	$n_{A1}^{V} = 0$	$n_{A2}^{V} = 1$	$n_{A3}^{V} = 0$	$n_{AP}^{V} = 0$	$n_{NP}^{V} = 0$	$n_{ND}^{V} = 1$	$\boldsymbol{n_{AN}^{V} = 2}$
In total		$n_{A1} = 31$	$n_{A2} = 61$	$n_{A3} = 19$	$n_{AP} = 620$	$n_{NP} = 145$	$n_{ND} = 164$	$\boldsymbol{n_{AN} = 1{,}040}$
		$n_A = 731$				$n_N = 309$		

Explanations: n – the number of sources of mine water assigned to a certain class of quantity ($^{\text{superscript}}$) and quality ($_{\text{subscript}}$). Other indicators the same as in Table 6.7.

From the evaluation of the place of occurrence of the most important mining-deposit regions of Slovakia the Gemer zone is the most prominent, both in terms of the total amount of documented mining waters and in terms of their frequency. The region hosts 63% of the total resources of mine water and 37% of their yield summary (Table 6.2). The quality classes A1, A2 and A3, which are satisfactory for drinking purposes, involve 126 $l \cdot s^{-1}$ documented mine water (Table 6.7), and in further sources with total yield of 272 $l \cdot s^{-1}$ satisfactory quality can be assumed (quality category AP). The second significant region – Central Slovakia Neovolcanites – total amount of mine water is slightly lower (26% of the total), but the frequency is much less represented (18%). In this region we register sources qualitatively suitable for drinking purpose of a total yield of only 17 $l \cdot s^{-1}$ and probably satisfactory in the amount of 47 $l \cdot s^{-1}$, while up to 396 $l \cdot s^{-1}$ is assigned – mainly due to the extremely high yield of the Voznica Drainage Gallery (MD 7-6) – into NO class with proven improper quality. Among the other regions particularly significant in terms of quantities documented mining water are the regions of Upper Nitra and Nízke Tatry Mts. A graphical comparison of the frequency and yield of documented sources of mine water by deposit-hydrogeological types and regional data is in Figs. 6.3 and 6.4.

Tab. 6.9 Documented quantities of mine water in $l \cdot s^{-1}$ in mining – deposit regions according to quality classes

Region	Q_{A1}	Q_{A2}	Q_{A3}	Q_{AP}	Q_{NP}	Q_{NO}	Q_{A}	Q_{N}	Q_{Σ}
1 Malé Karpaty Mts.	0	0	0	1.29	34.00	15.38	1.29	49.38	50.67
2 Záhorská nížina Lowland	0	0	0	25	0	0	25	0	25
3 Považský Inovec Mts.	0	0	0	9	0	0	9	0	9
4 Strážovské vrchy Mts.	0	0	0	0.1	0.72	0	0.1	0.72	0.82
5 Upper Nitra Basin	0	219.7	0	0.15	57	57	219.85	114	333.85
6 Tribeč Mts.	2.7	0	0	8.22	0	0	10.92	0	10.92
7 Central Slovakia Neovolcanites	2.95	14.31	0.18	47.32	0	396.18	64.76	396.18	460.94
8 Nízke Tatry Mts.	1.04	3.52	0	3.27	33.52	87.94	7.83	121.46	129.29
9 Juhoslovenská nížina Lowland	0	0	0	75	0	0	75	0	75
10 Vepor zone	0.03	5.38	0	5.81	3.13	3.37	11.22	6.5	17.72
11 Popradská and Hornádska Basins	0	0	0	0	0	8.16	0	8.16	8.16
12 Gemer zone	19.07	70.71	36.21	272.27	43.19	220.92	398.26	264.11	662.37
13 Šariš region	0	5.23	0	0.92	2.09	5.32	6.15	7.41	13.56
14 Vihorlatské vrchy Mts.	0	0.05	0	0	2.1	0	0.05	2.1	2.15

Explanations to symbols are stated in Table 6.7.

Table 6.10 shows categorisation of documented quantities of mine water by deposit-hydrogeological types. The most significant in terms of the total amount of documented amount are mine waters bound to deposits of siderite-sulphide mineralisation (*sz*) and the precious metal and polymetallic mineralisation of neovolcanites (*z*). To these types of deposits binds total yield Q_{Σ} of approximately 0.47 $m^3 \cdot s^{-1}$ of mine water, while at the deposits of the type *sz* there are 554 sources and the type *z* 195 sources. The comparatively high overall yield of mining water is bound to only 10 sources in coal deposits (*uh*). Relatively high total yield of 143 $l \cdot s^{-1}$ have 139 sources on stibnite veins (*az*), while for other types of deposits their total amount does not exceed the level of 60 $l \cdot s^{-1}$.

Tab. 6.10 Documented quantities of mine water in $l \cdot s^{-1}$ according hydrogeological types of deposits and quality classes

Deposit type	Q_{A1}	Q_{A2}	Q_{A3}	Q_{AP}	Q_{NP}	Q_{NO}	Q_A	Q_N	Q_{AN}
phm	0	15.11	0	3.04	0	0	18.15	0	**18.15**
ssu	0	1.52	0	0	29.48	24.46	1.52	53.94	**55.46**
u	6.77	10.41	0	15.05	15.15	7.34	32.23	22.49	**54.72**
sche	0	3.05	0	2.5	0.31	33.86	5.55	34.17	**39.72**
az	2.17	0.57	0.08	0	59.4	80.72	2.82	140.12	**142.94**
sz	8.12	27.57	36.13	247.73	0	153.2	319.55	153.2	**472.75**
mz	0.03	0.9	0	0	8.2	7.39	0.93	15.59	**16.52**
sid	3.0	10	0	0.05	1.02	7.41	13.05	8.43	**21.48**
mag	0.05	6.0	0	12.1	0	0.48	18.15	0.48	**18.63**
mst	0	4.48	0	3.33	0	2.55	7.81	2.55	**10.36**
sa	0	0	0	0	0	10	0	10	**10**
mn	0	0	0	1.29	0	8.16	1.29	8.16	**9.45**
z	5.65	19.54	0.18	52.11	0	394.25	77.48	394.25	**471.73**
i	0	0	0	0.2	4.19	7.24	0.2	11.43	**11.63**
lim	0	0.05	0	1.75	1	0.2	1.8	1.2	**3**
uh	0	219.7	0	103.2	57	57	322.9	114	**436.9**
sol	0	0	0	0	0	0.01	0	0.01	**0.01**
zlt	0	0	0	6	0	0	6	0	**6**

Explanation: Codes of deposit type according to Table 6.3. Classes of water quality according to Table 6.7.

6.5 The environmental problems related to mining water

Currently in Slovakia mining is underway only in 12 underground mines and from the environmental point of view it is a subject to strict control, in accordance with national legislation that is approximated to EU legislation. Environmental problems therefore relate in particular to the numerous abandoned mines and particular threat of contamination of water and sediment of the surface flows with heavy metals, which are loaded in mining water. In recent years, dangerous inrushes of mine water from abandoned mines have been experienced locally.

6.5.1 Mine water as a source of surface water contamination

Mine water freely flowing from abandoned mines or pumped during their drainage, according to local conditions can affect the quality of surface water. The negative influence of surface water in Slovakia was confirmed at several locations (e.g. Bačová, 2001; Lintnerová et al., 2004; Bajtoš, 2009 and 2012; Chovan et al., 2010; Ženišová et al., 2015). Since 2007, the state monitoring of the effects of mining on the environment takes place on the selected risk areas; in the scope of the project the effect on the quality of surface water is pursued (Bajtoš et al., 2012).

To obtain a regional overview and to identify other possible sources of contamination, we evaluated the results of laboratory analyses of mine water collected in a database. We defined the characteristic values (typical value – TV) of water quality indicators and compared them with the limits (required value – RV) under Government Regulation no. 269/2010 Coll., which stipulates the quality of surface waters. From the results of this assessment it follows, that the most common risk pose increased concentrations of arsenic (35% of the evaluated cases), antimony (33%), copper

(31%), zinc and manganese (over 29%) and too low value of dissolved oxygen (29%). Other potential contaminants are: sulphate anion (18%), mercury (17%), calcium (16%), nickel, iron and aluminium (14%), or pH (12%). In less than 10% of the cases as potential contaminants act nitrite nitrogen, ammonium nitrogen, cadmium, chromium, cobalt, lead, silver, magnesium and sodium.

Ongoing monitoring of risk sites affected by mining activity is documented by the continuing adverse impact of the presence of mined deposits on surface water quality (Table 6.11). Given the rapid circulation of groundwater in near-surface zone of the hydrogeological massif of Palaeozoic metamorphic rocks in the areas affected by ore deposits mining in Gemer region (sites Rudňany, Nižná Slaná, Slovinky, Rožňava, Smolník, Novoveská Huta), the components released by weathering of minerals quickly get into local surface waters and they impair their quality. The worst situation is at the site Smolník (MD 12-16), where the water of Smolnícky potok Creek in the profile below the deposit is contaminated by Fe, Mn, Al, Zn and Cu, with a high excess of the limit values (Table 6.12). Said elements are brought in to the stream by acid mine water and leachate from a flooded pyrite mine. Results of the mass flow balance at the Smolník site showed (Bajtoš et al., 2013) that 3.92 to 9.82 tons of sulphate anions; 0.34 to 1.04 tons of iron; 37.6 to 107.6 kg of manganese; 69.1 to 300.7 kg of aluminium; 9.0 to 32.6 kg of zinc; and 1.2 to 25.9 kg of copper is released daily as dissolved solids into the stream water. Most of this originates in the monitored objects (Pech Shaft, Karoli Adit, Nová Adit, and two drainage effluents from settling pit): 55 to 79% of SO_4; 39 to 100% of Fe; 44 to 79% of Mn; 27 to 100% of Al; 38 to 93% of Zn; and 26 to 100% of Cu. The primary source of contamination is the mine water discharged from the Pech Shaft, which releases more than 90% of SO_4 and Mn, and more than 99% of Fe, Al, Zn and Cu. In the Slovinský potok Creek, in the profile below the deposit Slovinky (MD 12-10) the content of Sb varies in the range 6 – 20 $\mu g \cdot l^{-1}$. The results of the balance of Sb in the waters of Slovinky showed that in the period between 2008 – 2011 the mass flow of this element varied in the range of 264 – 772 $g \cdot d^{-1}$. Increase of the Sb amount in the stream coming from the balancing area was 217 – 544 $g \cdot d^{-1}$. Only a small fraction of this amount (9 – 58 $g \cdot d^{-1}$) represented antimony loaded in mining water of the Alžbeta Gallery (main drainage work on the deposit). The summary amount of Sb carried in water from the Alžbeta Gallery and seepage water from the tailings represent only 15 – 91 $g \cdot d^{-1}$ (Bajtoš, 2012a). Therefore, the main source of Sb in the water stream in the Slovinský potok Creek in the Slovinky area not the most important monitored objects with mining water and the drainage of the tailing ponds, but probably smaller sources and mining leachate scattered in the area, or soil contaminated by air pollution from thermal operations in Krompachy. In contrast, these monitored objects are the major sources of arsenic contaminating the Slovinský potok Creek.

At the site Rudňany (MD 12-3) the main contaminant of water of Rudniansky potok Creek is antimony, which concentration averages 10 $\mu g \cdot s^{-1}$. About a quarter of the amount of mining water contribution comes from the Rochus Gallery, flowing out from flooded Fe, Cu mine. At the site Rožňava (MD12-13) the contaminated mine waters from the galleries are sufficiently diluted in terms of the required water quality of the Slaná River, as regards the content of potentially toxic metals As, Sb, Ni, Zn and Cu. The risk pose iron and manganese in the period of lower flow of the Slaná River, which may cause deterioration in the quality of the river water. At the site Novoveská Huta (12-1) mine waters only locally worsen the water quality of local streams, while its radiological indicators are satisfactory despite of present uranium deposit positions.

Significantly contaminated are surface streams on the locations Dúbrava, Pezinok and Špania Dolina. The amount of antimony entering in the Paludžanka stream at the abandoned antimony deposit Dúbrava (MD 8-9) in dissolved form, determined on the basis of balance measurements repeated for seven times in the years 2008 to 2011, reached here 4.5 – 15.3 $kg \cdot d^{-1}$ (more than 2 tonnes per year), whereby an average of 74% share of this amount is linked to the water flowing from 6 mining galleries (Bajtoš, 2012). The water of Blatina Creek in the profile below the Sb deposit, in front of the inlet to the urban area of Pezinok (MD 1-2) contains on average 7 times higher concentrations of Sb and As, as appropriate limit values for surface water. The dominant source of contamination are mine waters from three galleries. At the site Špania Dolina (8-1) with a historical mining of copper veins (*mz*), in the waters of the Banský potok Creek, Richtársky potok Creek and Zelená Creek the monitoring documented greatly exceeded limit value of Cu (5 – 6 to 80 fold), Sb (19 –1 2 – 128 fold) and As (5 – 1.3 – 6 times), largely due to mine water of the old galleries.

The most important source of contamination at the site Banská Štiavnica (MD 9-6) is mine water of the Voznica Heritage Gallery (VDS) and New Drainage Gallery (NOŠ), which drain almost entire Štiavnica-Hodruša ore district. Mass flow rate of zinc dissolved in the VDS water amounts to 75 – 160 $kg \cdot d^{-1}$, manganese 60 – 100 $kg \cdot d^{-1}$, cadmium 0.2 – 0.5 $kg \cdot d^{-1}$. Mass flow rate of zinc from NOŠ is approximately 0.5 $kg \cdot d^{-1}$. Model calculations indicate that the zinc content in the Hron River below the VDS and NOŠ mine water inflows tends to be higher than the desired value for most of the year – mostly in the winter, summer and autumn. The expected concentrations of cadmium, nickel, copper and lead in the Hron River below the adit collar of VDŠ and NOŠ are below required levels.

In the Upper Nitra area the chemical composition of surface water is affected by discharged mine water draining the coal deposits. They cause increase in the concentration of sulphates (also TDS), iron, manganese and arsenic. The rate of increase does not cause unacceptable deterioration in the quality of local watercourses. Among the four mining water discharges only water from the gallery in Lehota pod Vtáčnikom exceeds the limit values for arsenic. Increased levels of NO_2 and Hg, documented in monitored surface flows don’t originate from the mine water of the coal deposits.

Tab. 6.11 Indicators which do not meet the requirements of Government Ordinance SR No. 269/2010 Coll. for surface water quality and risk criteria of groundwater quality by Guideline of MoE SR 1/2012-7 detected at monitoring sites in the period from 2007 to 2014 (Bajtoš et al., 2015)

Site	MD number	Deposit type	Parameters not meeting criteria for surface water quality	
			Mine water, drainage water from tailing ponds	Surface streams
Upper Nitra	5-2	*uh*	NO_2, Mn, Hg, As	NO_2, As, Hg
B.Štiavnica-Hodruša	7-6	*z*	EC, SO_4, Fe, Mn, Al, Zn, Pb, Cu, Cd, Ca, NO_2	Zn, NO_2
Kremnica	7-7	*z*	SO_4, Mn, Zn, As, Sb, Cu	As
Dúbrava	8-9	*az*	Sb, As	Sb, As
Pezinok	1-2	*az, ssu*	EC, SO_4, Fe, Mn, Zn, As, Sb, Ni, Cd	Sb, As
Špania Dolina	8-1	*mz*	SO_4, Zn, As, Sb, Cu	As, Sb, Cu
Rudňany	12-5	*sz*	EC, SO_4, Mn, Hg, Sb, Ba	Sb, Cu, Mn
Nižná Slaná	12-17	*sid*	SO_4, Mn, As	
Slovinky	12-10	*sz*	EC, SO_4, Mn, As, Sb, Cu, Ni, Co	As, Sb, Cu
Rožňava	12-13	*sz*	EC, pH, SO_4, Fe, Mn, Al, Hg, Zn, As, Sb, Cu, Ni	
Smolník	12-16	*ssu*	EC, pH, SO_4, Fe, Mn, Al, Hg, Zn, Pb, As, Cu, Ni, Co, Cd	pH, Fe, Mn, Al, Zn, Cu
Novoveská Huta	12-1	*u, sz, sa*	EC, RL, SO_4, As, Sb, Cu, Ca	EC, RL, SO_4, Mn, Cu, Al, Ca

Tab. 6.12 A comparison of the characteristic values of water quality parameters at the Smolník area with quality requirements for surface water (2008 – 2013)

Object	Value	EC	pH	SO_4	Fe	Mn	Al	Hg	Zn	Pb	As	Cu	Ni
Sm1	TV	10.4	7.26	16	0.34	0.06	0.05	<0.1	26	3	2	6	1
	TV/RV	0.20	V	0.06	0.16	0.19	0.22	0.50	0.75	0.39	0.15	0.20	0.04
Sm8	TV	32.5	**6.14**	142	**13.29**	**1.46**	**2.67**	<0.1	**405**	5	7	**134**	12
	TV/RV	0.28	**N**	0.54	**6.09**	**4.50**	**11.52**	0.50	**12.08**	0.53	0.67	**4.57**	0.39

Explanations: Sm1 – Smolnícky potok Creek deposit upstream, Sm8 – Smolnícky potok Creek below deposit. Specifications TV/RV represent the share of determined characteristic values of quality indicator (typical value – TV) for the reporting period and the setpoint (required value – RV) according to the SR Government Ordinance No 269/2010 Coll . Values greater than 1 mean the exceeded required values.

Increased concentrations of contaminants released in the aqueous solution from the ground disturbed by extraction cause contamination of sediments accumulated in local surface flows. The major contaminant elements at the monitored sites are arsenic and antimony; their content in sediments exceeded by the results of the one-shot sampling in 2012 the intervention criterion for the industry at all monitored ore mining sites with the exception of Novoveská Huta (Table 6.13). Further documented risk contaminants in stream sediment are Pb, Zn, Cd, Hg, As, Cu.

Among the sites that are not monitored under the state Monitoring of the effects of mining on the environment significant negative impact on the quality of surface water is documented mainly in Dubník in Slanské vrchy Mts. (MD 13-3 Dubník). Surface water of Jedľovec Creek is here contaminated by compounds carried in the mine water (Bajtoš & Cicmanová, 2005). The pH of the water stream is in the range from 3.01 to 3.48, the concentration of the aluminum ranges from 14 do 20 $mg \cdot l^{-1}$, so it is 70 to 100 times higher than RV for surface water and the content of Zn 77 – 101 $\mu g \cdot l^{-1}$ exceeds the RV 7 – 10-fold. The contents of other polluting components (Fe, Mn, SO_4) are unsatisfactory only occasionally. The results of the acute ecotoxicity samples of mine water from the Slávik Gallery and surface water of the Jedľovec Creek showed that these waters are toxic to aquatic organisms (Cicmanová & Lučivjanská, in Bajtoš et al., 2003).

The above regional evaluation of mine water quality has allowed to identify other sites of high risk in terms of harm to the quality of surface water by discharges of mining water. Antimony contamination poses a risk in Jasenie location in the Nízke Tatry Mts. (MD 8-5), where the water from the galleries no. 3 and no. 4 reaches the concentration of this metal 0.09 or 0.06 $mg \cdot l^{-1}$ at daily summary 0.2 kg. Sb. Daily released amount of arsenic reaches 2 kg. The next location in the Nízke Tatry Mts. is Magurka (MD 8-6),

Fig. 6.5 Mouth of Dolnosirkovská Gallery near Sirk with intense Fe-ochre formation.

where only from the Gallery Dedičná Russeger escapes daily about 0.2 kg Sb. In the Central Slovak Neovolcanites there are several galleries with high contents of metals. Through the Gallery Neufang Dedičná in Nová Baňa (MD 7-4) daily mass discharge in mine water equals to ca 0.1 kg As, 0.01 kg Ni and 4 kg Fe, through the Gallery Anna Božena in Rudno nad Hronom (MD 7-5) 43 kg Fe, 22 kg Al, 3 kg Mn, 4 kg Zn and 0.02 kg Cu. In Ľubietová in Veporicum Zone (MD 10-2) about 0.15 kg·d^{-1} of copper escape in mine water. Dolnosirkovská Gallery (Fig. 6. 5) in Sirk (12-19) in Gemer zone releases 20 kg Fe, 37 kg Mn and 0.1 kg Ni a day.

6.5.2 Inrushes of mine water from abandoned mine workings

A specific problem in the last years in Slovakia is the danger of sudden inrushes of mine water from the adit collars of the abandoned workings localised over inhabited areas or directly in them. The most dangerous situation occurred in Novoveská Huta (MD Gemer zone, MD 12-1: Novoveská Huta – Hanisková) where the evaporite overburden caving-in sealed the passage of the Nová Gallery, leading to increase in the water column due to inflowing of mine water with consequent gradual enlargement of the accrued amount. Sudden break of this collapsed material by water due to high hydrostatic pressure caused the formation of extreme discharge waves, which after reaching the surface ruined adit collar of the gallery (Fig. 6.6), damaged the road leading to the Nová Gallery (Fig. 6.7) and also caused damage in the gardens and the houses of Teplička residents in the catchment of Tepličský Brusník Creek. The unexpected outburst of mine water occurred also in Gelnica, part Turzov (MR Gemer zone, MD 12-10 Slovinky – Gelnica). This mine (mine-deposit type *sz*) has been abandoned since 1993 (Bajtoš et al., 2011b) and this was for the first time that such event occurred. According to information publicized water suddenly surged 3.6.2010 morning from the adit collar of Stará Krížová Gallery and flooded the local land and damaged local roads. During this flood risk period there were observed extremely high yields of local galleries, accompanied by the risk phenomena, and the inhabitants of the Zlatá Idka (MR Gemer zone, MD 12-18 Čučma – Bystrý potok – Poproč – Zlatá Idka). In 2005, the outpouring of water from the Slávik Gallery at Dubník (MD 13-3 Dubník) eroded part of the heap and polluted creek Jedľovec with 400 m^3 of sediment with high mercury content.

The conditions and the course of these events were analysed in the context of geo-environmental studies (Bajtoš et al., 2011b), which were followed by risk analysis. The existing estuaries of workings were assessed as potentially dangerous in terms of mine water inrushes. Discharges of

Tab. 6.13 Indicators of sediment quality which do not meet the criteria by Guideline of MoE SR 1/2012-7 for the rock environment and soil found at monitoring sites in the period from 2007 to 2013

Site	Indicators exceeding indicative criterion	Indicators exceeding intervention criterion for residential zones	Indicators exceeding intervention criterion for industrial zones
Upper Nitra	As	As	As
B.Štiavnica-Hodruša	Pb, Zn, Cu, Cd, As, Sb, Hg	Pb, Zn, Cu, Cd, As	Pb, Zn, Cu, Cd
Kremnica	Zn, As, Sb, Co	As, Sb, Co	As
Dúbrava	As, Sb	As, Sb	As, Sb
Pezinok	As, Sb	As, Sb	As, Sb
Špania Dolina	Hg, As, Sb, Cu	As, Sb, Cu	As, Sb, Cu
Rudňany	Hg, As, Sb, Cu	Hg, As, Sb, Cu	Hg, Sb
Slovinky	Hg, As, Sb, Cu	As, Sb, Cu	As, Sb
Smolník	Pb, As, Sb, Cu	Pb, As, Sb, Cu	As, Sb
Novoveská Huta	-	-	-

Fig. 6.6 Mouth of Nová Gallery destroyed by mine water inrush from abandoned mine (photo Baláž).

Fig. 6.7 Local road eroded by flood wave of mine water inrush from Nová Gallery (photo Baláž)

water from the adit collars of the old workings occur in the land of 147 settlements. Most of them are located in Spiš-Gemer Ore Mountains (MR12) and Štiavnica-Hodruša ore district (MD 7-6). Within the municipalities there are 150 sources of mine water, out of which 82 can be considered as potentially high-risky, requiring closer examination of the status in order to propose measures to eliminate the risk.

6.6. Discussion

Mining waters are characterized by high variability of the chemical composition, even within the allocated hydrogeological types of deposits. Therefore, even in a single mine-deposit region or even a single deposit sources can often be found next to each other inconvenient but also meeting the quality requirements for drinking water. Their yield is usually higher than the yield of natural springs of groundwater at the site; hence they are interesting in quantitative terms to use.

In terms of water management potential of mine water use the most promising among mining-deposit regions of Slovakia's is the Gemer zone region (Spiš - Gemer Ore Mountains). Currently there are 21 local water sources of mine waters of summary yield of approximately 25 $l \cdot s^{-1}$, which represents 8% of the total amount documented. In Štiavnica-Hodruša mining district there are registered 16.6 $l.s^{-1}$ of exploitable amounts of mine water (Viest, 1993) and water-managed are outflows from 8 galleries with a total yield of 19.0 $l \cdot s^{-1}$. Other exploited mine water sources can be found in Pukanec (MD 7-5) and at Kokava (MD 10-7). Local discharges from abandoned galleries are potential water sources of local importance that in the present dispersed nature of settlement may be interesting objects to use for local self-government bodies, legal entities and individuals. The most significant factor limiting their wider use for drinking purposes is quite common necessity of physico-chemical treatment due to elevated levels of some metals (especially Fe, Mn, Sb, As), more of the occasional than of the permanent nature. Provided cost-effective treatment technologies of such waters would be ensured, it could lead to a significant increase in the use of their exploitation. For example, at selected locations in the Gemer zone, at the VDŠ in Štiavnica-Hodruša ore district (MD 7-6) and the site Dubník (MD 13-3), it has been demonstrated high efficiency of natural sorbents in removing contaminants from the mine water (Kovaničová et al. 2014).

Presented overview of the regional mining water quality shows that in many locations in Slovakia the resources adversely affect the quality of surface water flows. Currently ongoing monitoring studies the size of this impact and its changes over time on the most risky locations. Although the sources of contamination have been known for a long time, no one of the abandoned mines has been equipped with a system for cleaning of contaminated mine water. This is primarily due to persisting under-financing because of non-existent object owner. In addition to contaminants in dissolved form the problems arise also from the formation of iron ochre and sediment rich in heavy metals. These are formed by precipitation of the mine water at the number of deposits, both in the underground and also in the mine water runoff trickles on the surface (Fig. 6. 8). The ochre formation in underground is usually very intense. At the siderite (type *sid*) deposit Železník in Sirk (MD 12-19) variations of this amount during the year, by measuring the yield of the mine water effluent from the Dolnosirkovská Gallery (Fig. 6. 5), laboratory analyses of mine water and geochemical modelling were estimated at 0.7 to 6.4 tons per day (Bajtoš, 2012b). Their precipitation in the form of ochre sediment or ochre coating of the sand-gravel fluvial sediments occur during lower water levels in the case of heavily contaminated mine water in the riverbed surface flow. Length of the stream section with the formation of ochre, which can be identified visually (Fig. 6. 9), changes over time in proportion of the dilution of the source of contamination by the recipient. The periods of high water levels and flooding lead to erosion and outwashing of ochre sediment and this load is transported downstream. Their deposition takes place at points of flow deceleration, the most favourable environment for the accumulation process are the reservoirs (Brehuv et al., 2007; Šestinová et al., 2006; Hucko, 2005). However, it must be recalled that elevated concentrations of metals in sediment flows and water basins don't originate exclusively from precipitates of mine water but also from precipitates in drainage water of tailing ponds and seepage through heaps, and during the rainfall periods they enter the streams thanks to water erosion of heaps and tailing ponds.

In addition to environmental contamination by toxic elements contained in mine waters in recent years a new phenomenon emerges of risk associated with mining water. The last few years, and particularly extreme rainfall in 2010 revealed the potential risk of experiencing sudden inrushes of mine water from abandoned mines that can cause damage to the linear structures, building structures, land and environment. In terms of prevention of damage and threats to the population it is appropriate in this context to focus attention on finding an effective method of identifying the objects of risk in terms of the mine water inrushes emergence, to identify risk objects in local municipalities and their vicinity

Fig. 6.8 Mouth of Budúcnosť Gallery near Pezinok with mine water discharge with precipitating Fe-ochre (photo Baláž).

Fig. 6.9 Inflow of mine water from Pech Shaft into Smolnícky potok Creek. The bottom is coated with Fe-ochre from seepage through dumps situated atop the Pech Shaft. Al-precipitates from mine water are indicated by pale stripe downstream

and to inform the local authorities, to suggest a method of their technical arrangements for prevention of that risk, or – where appropriate – to put into practice monitoring for early warning prior to accident. Currently, with the maintenance of the most important estuaries of drainage galleries is entitled the organization Rudné Bane, š. p. Banská Bystrica. In urgent cases, this company proceeds with the opening and renovation of collapsed adit collars, to ensure a controlled outflow of mine water (Figs. 6. 10, 11).

Fig. 6.10 Situation of caved-in adit collar of Všechsvätých Gallery in Rudňany prior to its opening and reconstruction.

6.7 Conclusions

Presented regional overview of the incidence and nature of mining waters in Slovakia captures a situation which changes in the long term, depending on fluctuations in the intensity of mining activities and the availability of mineral deposits of interest to mining. Since massive completion of the extraction of the Slovak ore deposits after 1990 they have emerged to the then (historic and modern) mine water discharges from abandoned mines with stable runoff dozens of new ones. In the future, the existing number of sources of mine water will change only slightly and the hydrological regime will change only in a few of them. It can be expected that the attention of experts dealing with the issue of mine water will be mainly focused on the elimination of their negative impact on water quality and sediment of surface flows, on the intensifying of their exploitation for drinking or household water purposes, or even on utilisation of their geothermal energy potential.

Fig. 6.11 Portal built in 2013 at former caved-in adit collar of Všechsvätých Gallery in Rudňany

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Anniversary volume

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Manuscript

Radvanský F., Slivka B., Viktor J. & Srnka T., 1985: Vein deposits of the Jedľovec nappe of Gemericum. Final report from the project SGR-geophysics. Manuscript-archive ŠGÚDŠ Spišská Nová Ves, 28.

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