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

Peter Malík, Jaromír Švasta, František Bottlik

State Geological Institute of Dionýz Štúr , Dpt. of Hydrogeology and Geothermal Energy, Mlynská dolina 1, 817 04 Bratislava 11, Slovak Republic; peter.malik@geology.sk; jaromir.svasta@geology.sk; frantisek.bottlik@geology.sk

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.

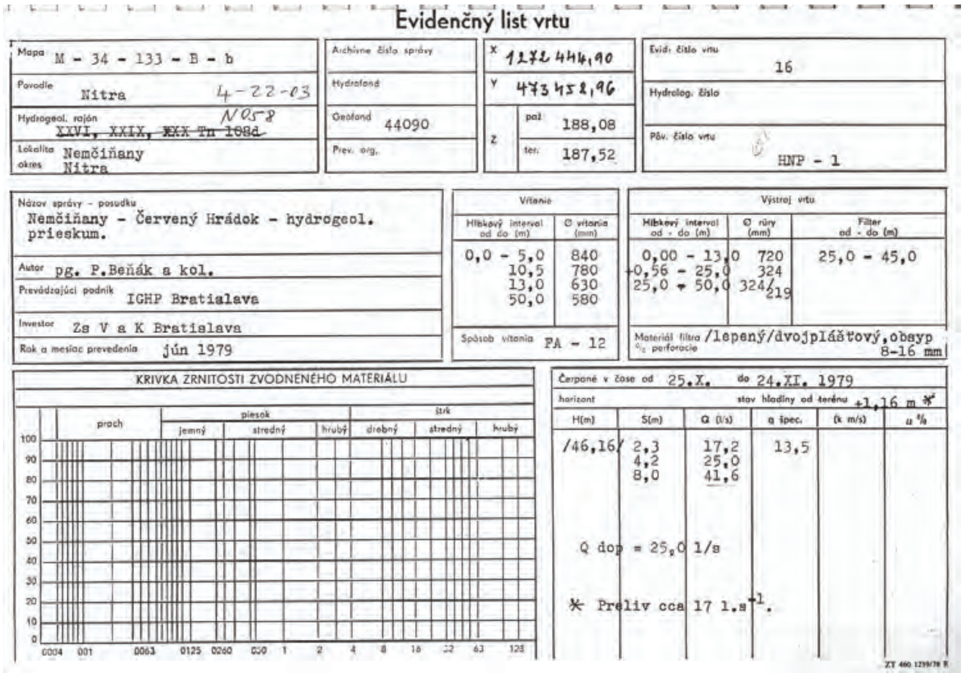
Keywords: hydrogeological boreholes, database of wells, specific capacity, transmissivity, hydraulic conductivity, Slovak West Carpathians

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 N 05 8
Lokalita okres Nemčiňany Nitra
Archívne číslo správy
Hydrofond
Geofond 44090
Prev. org.
X 1272444,90
Y 473452,96
Z pat 188,08 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

Vŕtanie
Hĺbkový interval od do (m): 0,0 - 5,0; 10,5; 13,0; 50,0
Ø vŕtania (mm): 840; 780; 630; 580
Spôsob vŕtania PA - 12

Výstroj vrtu
Hĺbkový interval od - do (m): 0,00 - 13,0; +0,56 - 25,0; 25,0 - 50,0
Ø rúry (mm): 720; 324; 324/219
Filter od - do (m): 25,0 - 45,0
Materiál filtra / perforácia: lepený/dvojplášťový,obsyp 8-16 mm

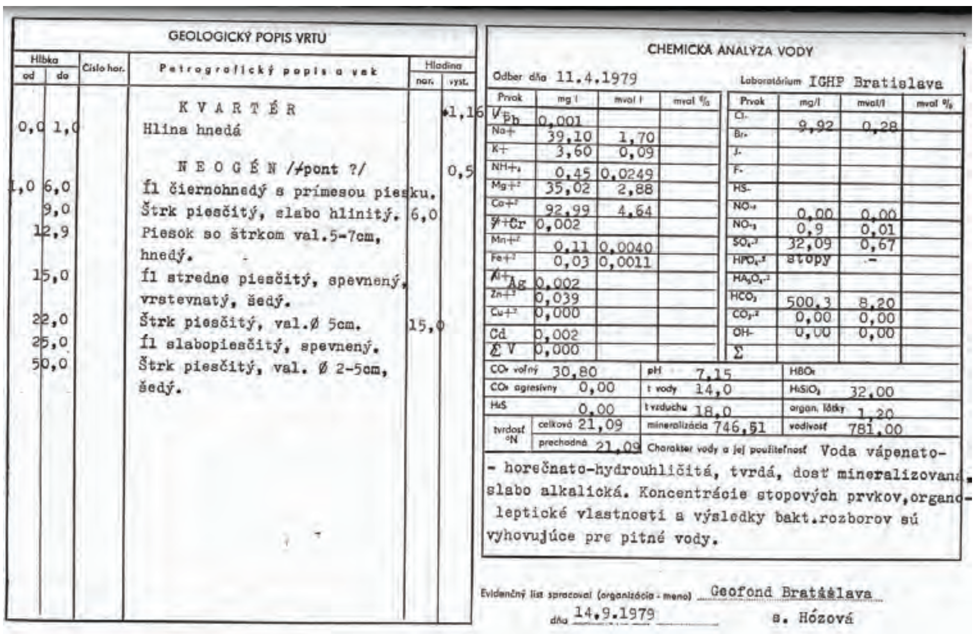
KRIVKA ZRNITOSTI ZVODNENÉHO MATERIÁLU

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)	a %
/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		Íl čiernohnedý s prímesou piesku.		
	9,0		Štrk piesčitý, slabo hlinitý.	6,0	
	12,9		Piesok so štrkom val.5-7cm, hnedý.		
	15,0		Íl stredne piesčitý, spevnený, vrstevnatý, šedý.		
	22,0		Štrk piesčitý, val.Ø 5cm.	15,0	
	25,0		Íl 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		H2AsO4-		
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.

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).

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,

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

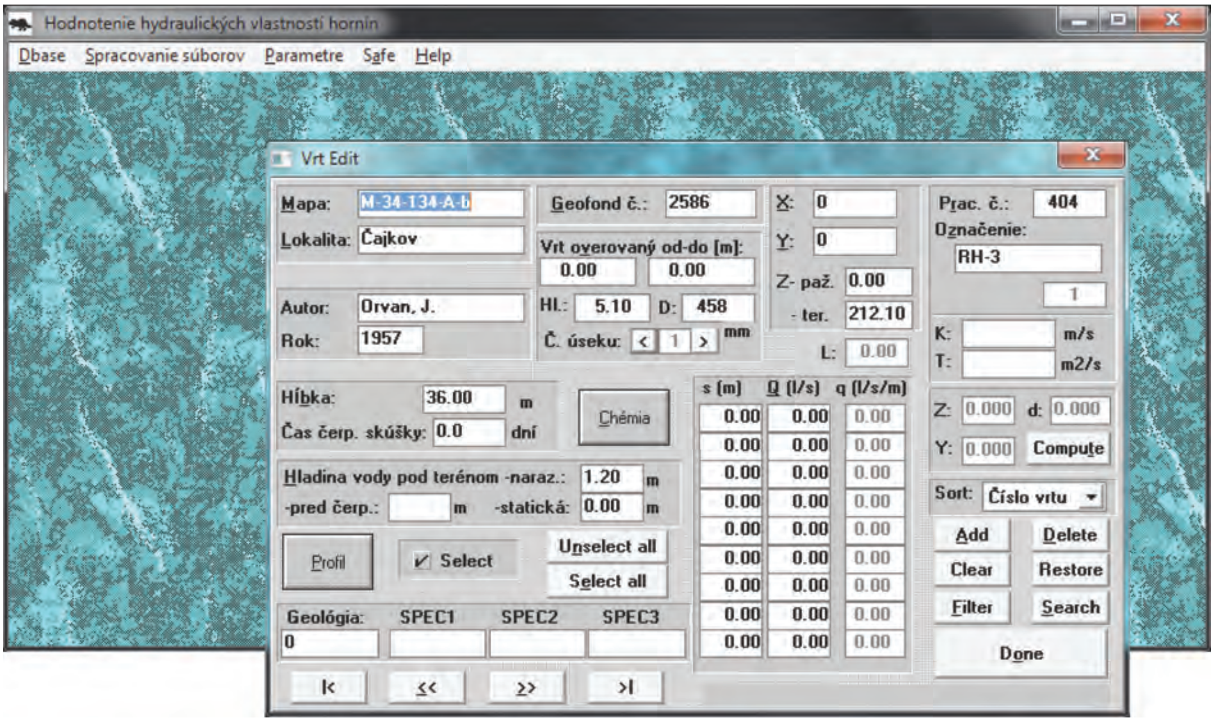


Fig. 3.3 User interface of HydroSis program.

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.

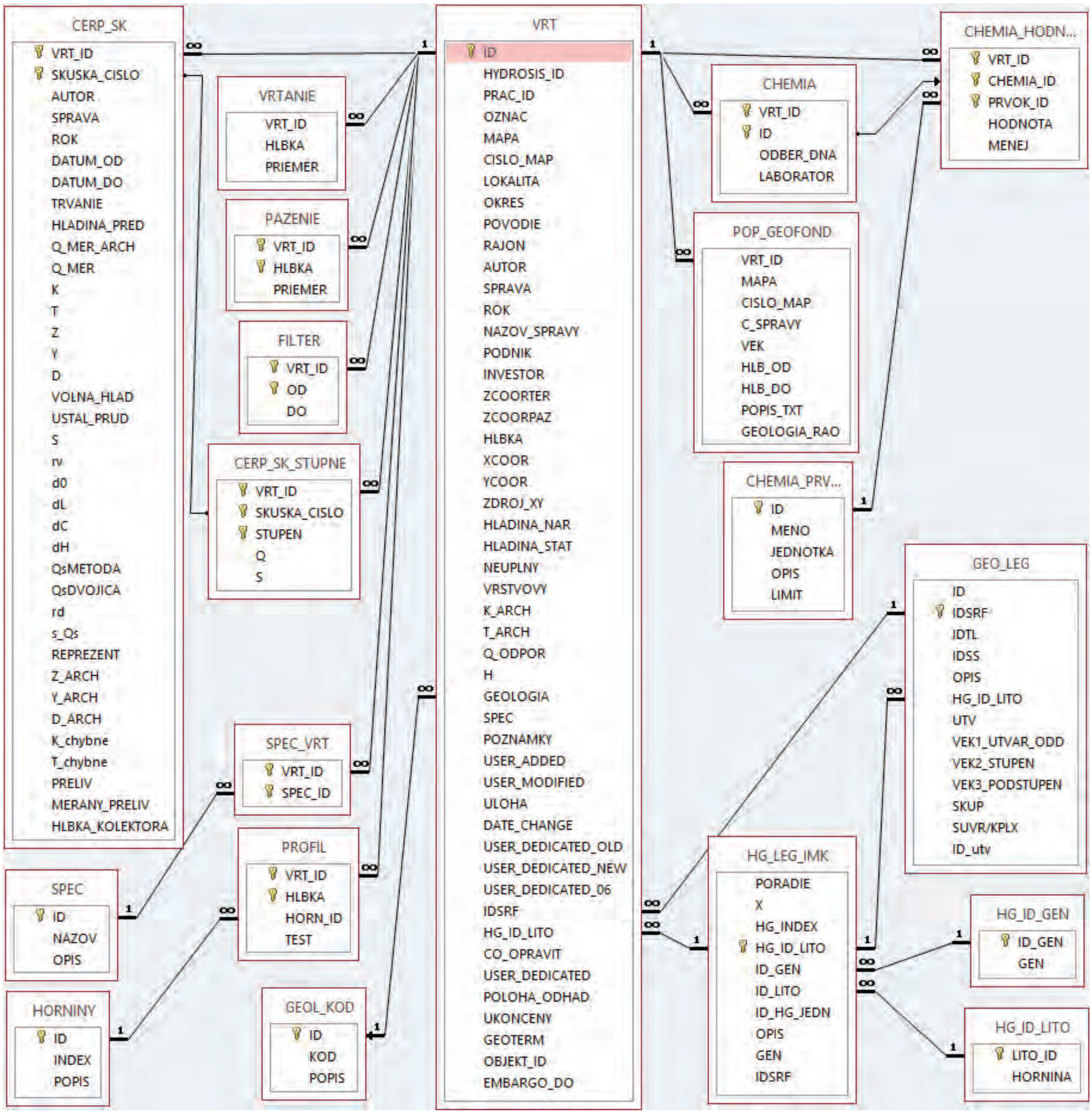


Fig. 3.4 Schematic diagram of the database structure, showing tables and their relations.

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:

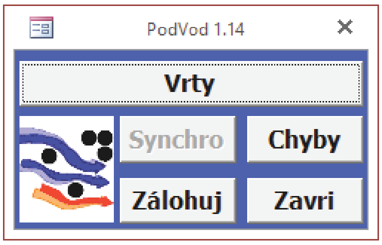


Fig. 3.5 Start-up dialog.

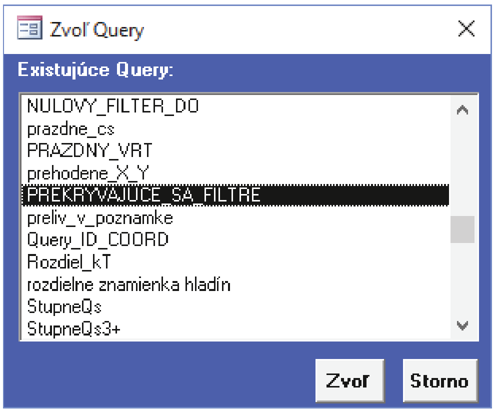


Fig. 3.7 Select query dialog.

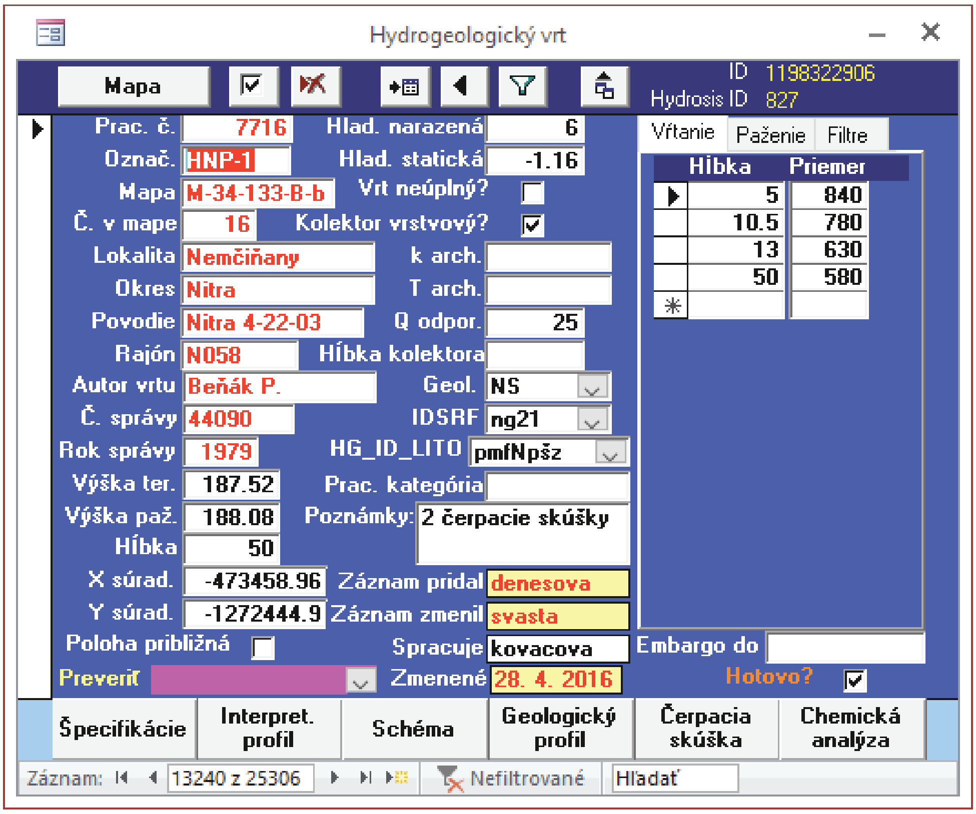


Fig. 3.6 Main form.

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.

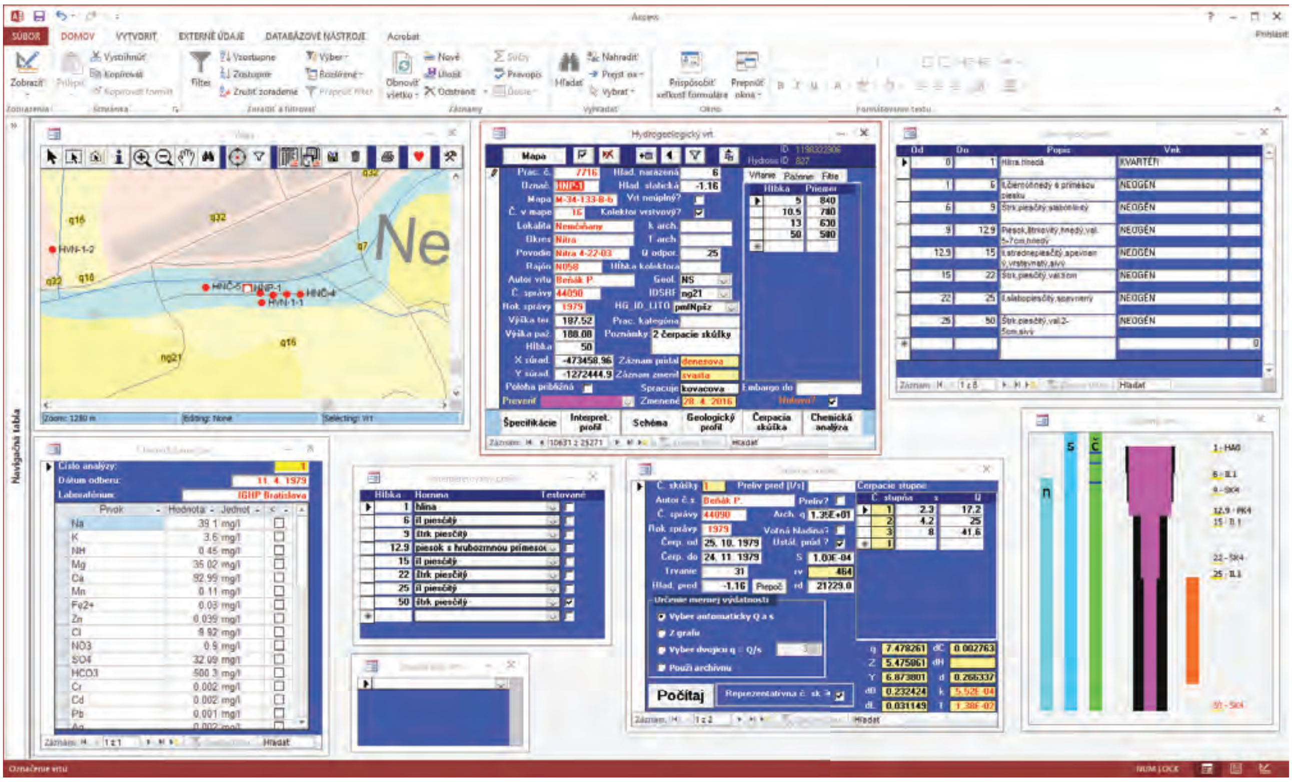


Fig. 3.8 Example of organizing forms in a user workspace.

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.

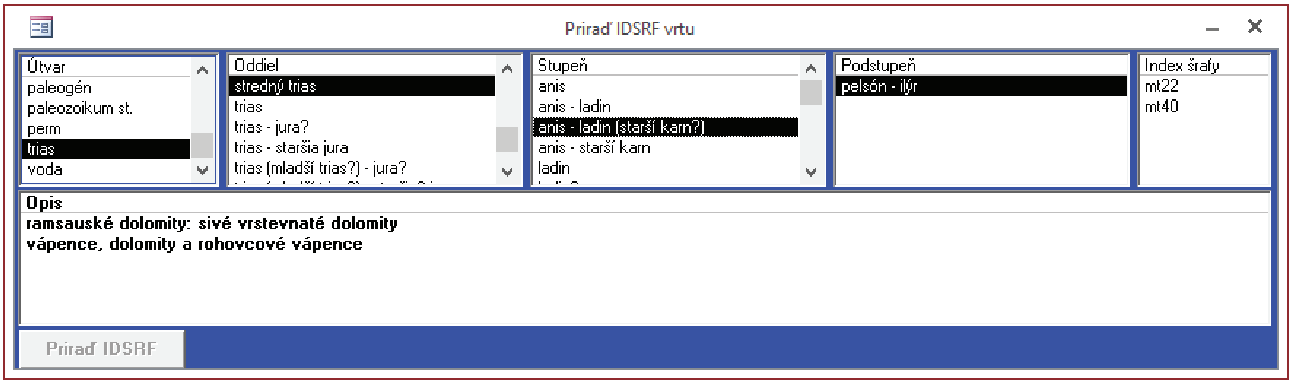


Fig. 3.10 Tool for stratigraphical and lithological characterisation of an aquifer.

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.

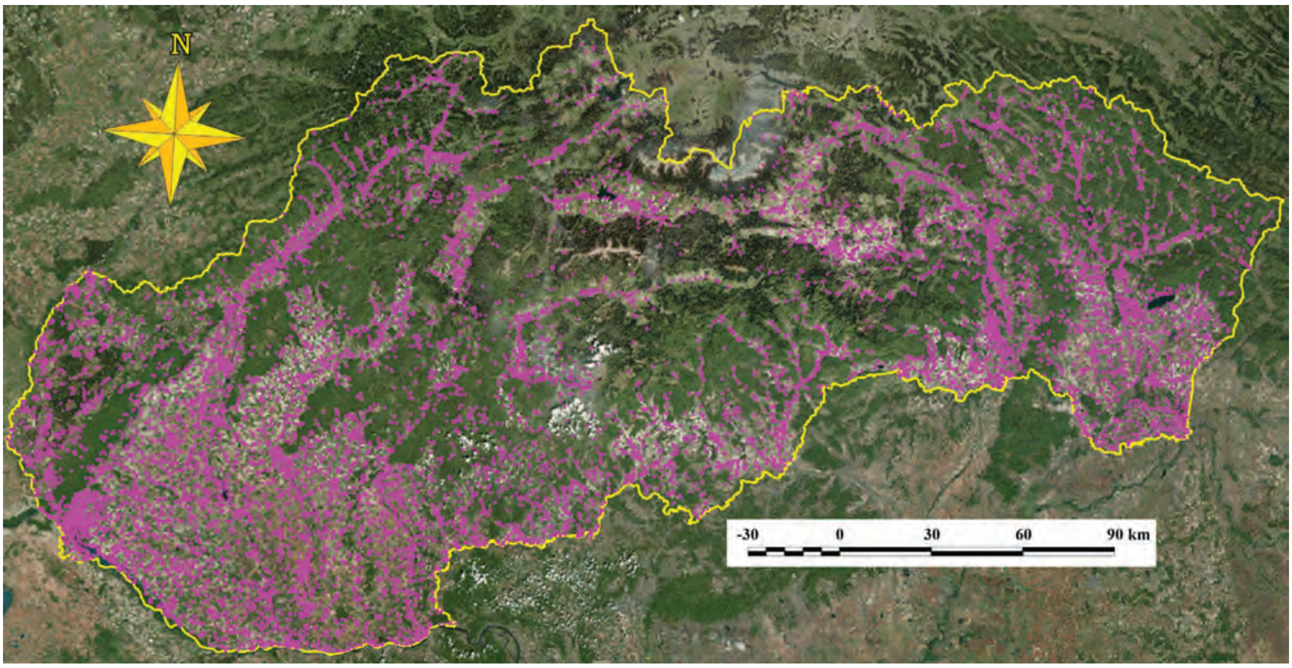


Fig. 3.11 Spatial distribution of 24,070 hydrogeological boreholes (violet dots) in Slovakia. Topography © ArcGIS World Imagery contributors.

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.

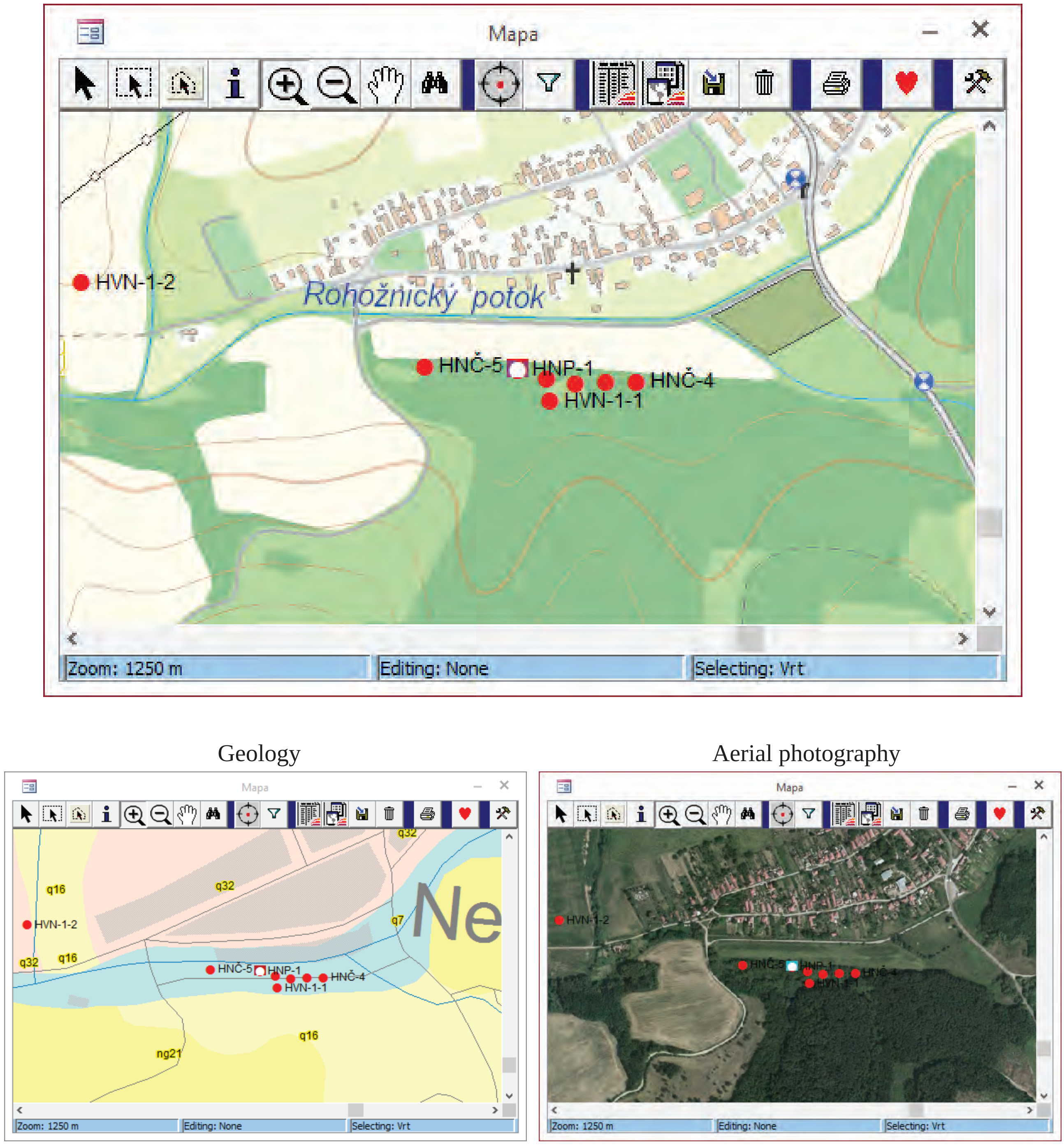
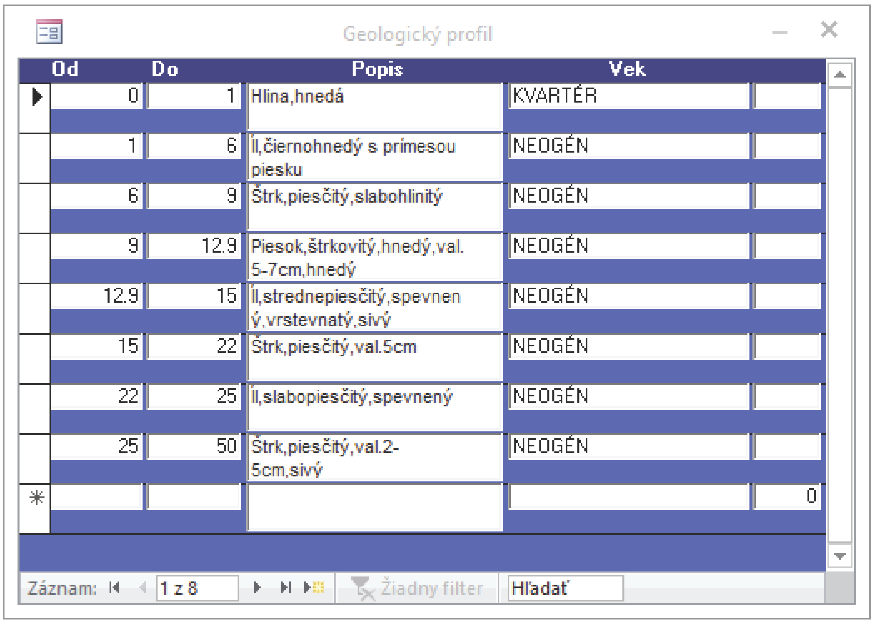


Fig. 3.12 Interactive map with boreholes (red) and different backgrounds (© Geological map of the Slovak Republic at 1:50,000, ZB-GIS® - Institute of Geodesy and Cartography Bratislava, National Forest Centre Zvolen).

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).



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

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.

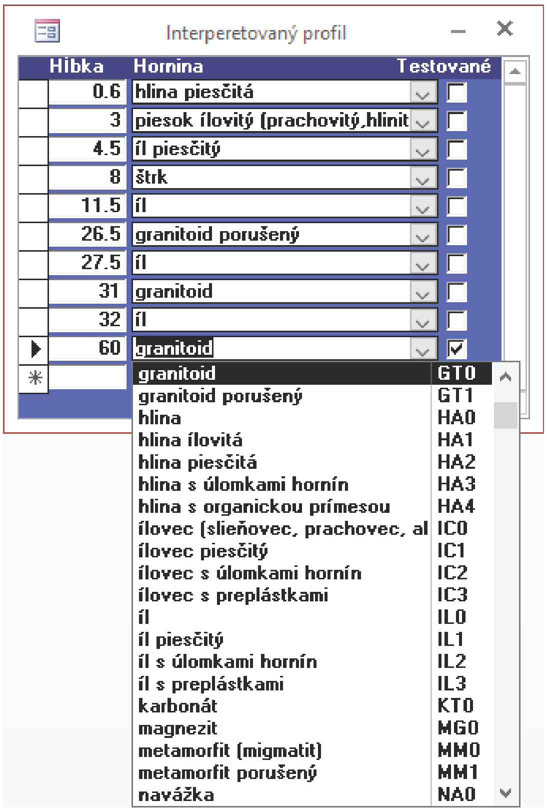


Fig. 3.14 Interpreted lithological profile form.

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.

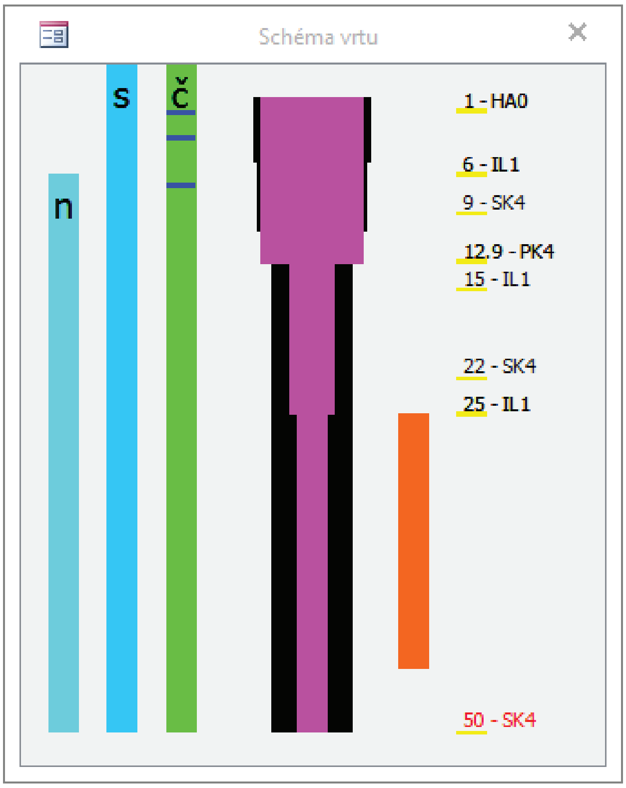


Fig. 3.15 Hydrogeological borehole schematic diagram.

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).

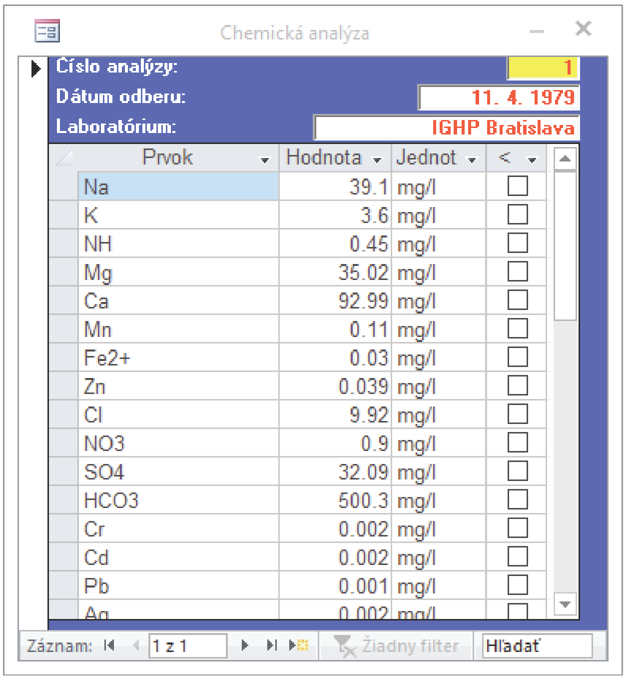


Fig. 3.16 Chemical analysis form.

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.

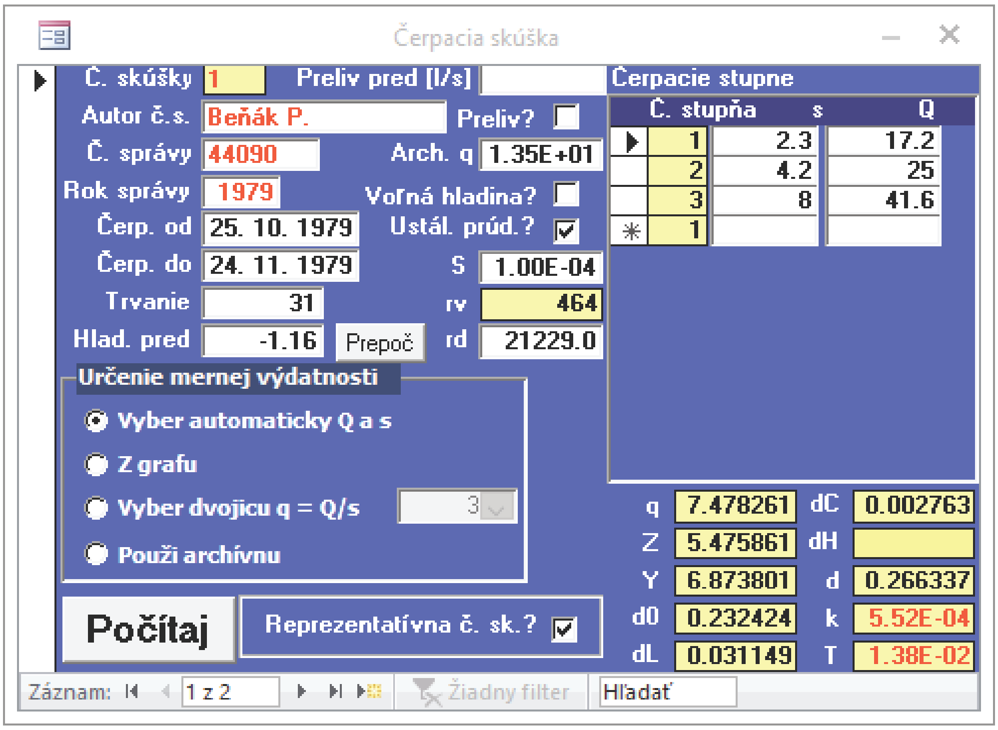


Fig. 3.17 Pumping test form layout.

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).

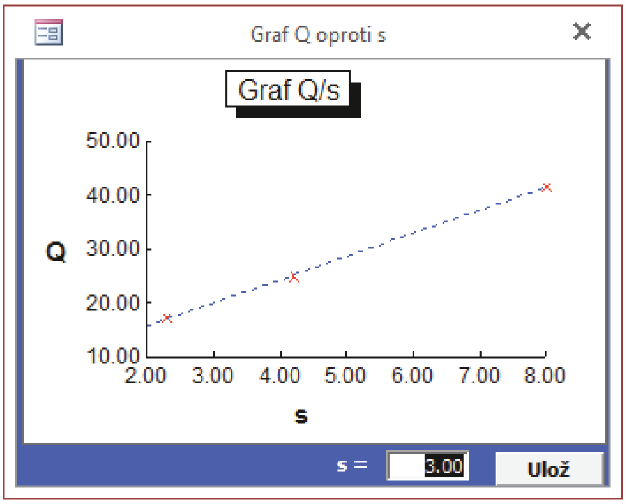


Fig. 3.18 Well yield (Q) vs. drawdown (s) relationship chart.

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):

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

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):

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

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):

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

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

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).

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

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):

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

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 ^1q_c should be used to calculate values of approximate logarithmical parameters ***Y*** and ***Z***. Value of ^1q_c is obtained according to the equation (9):

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

where:

^1q_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 ^1q 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:

$$d_z = d_S + d_X \quad (23)$$

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.

$$d_z = d - d_0 - d_L - d_c = d_s + d_x \quad (24)$$

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:

$$d = d_0 + d_L + d_C \quad (25)$$

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(¹q)	Md(¹q)	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(ᴵq)	Md(ᴵq)	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.*

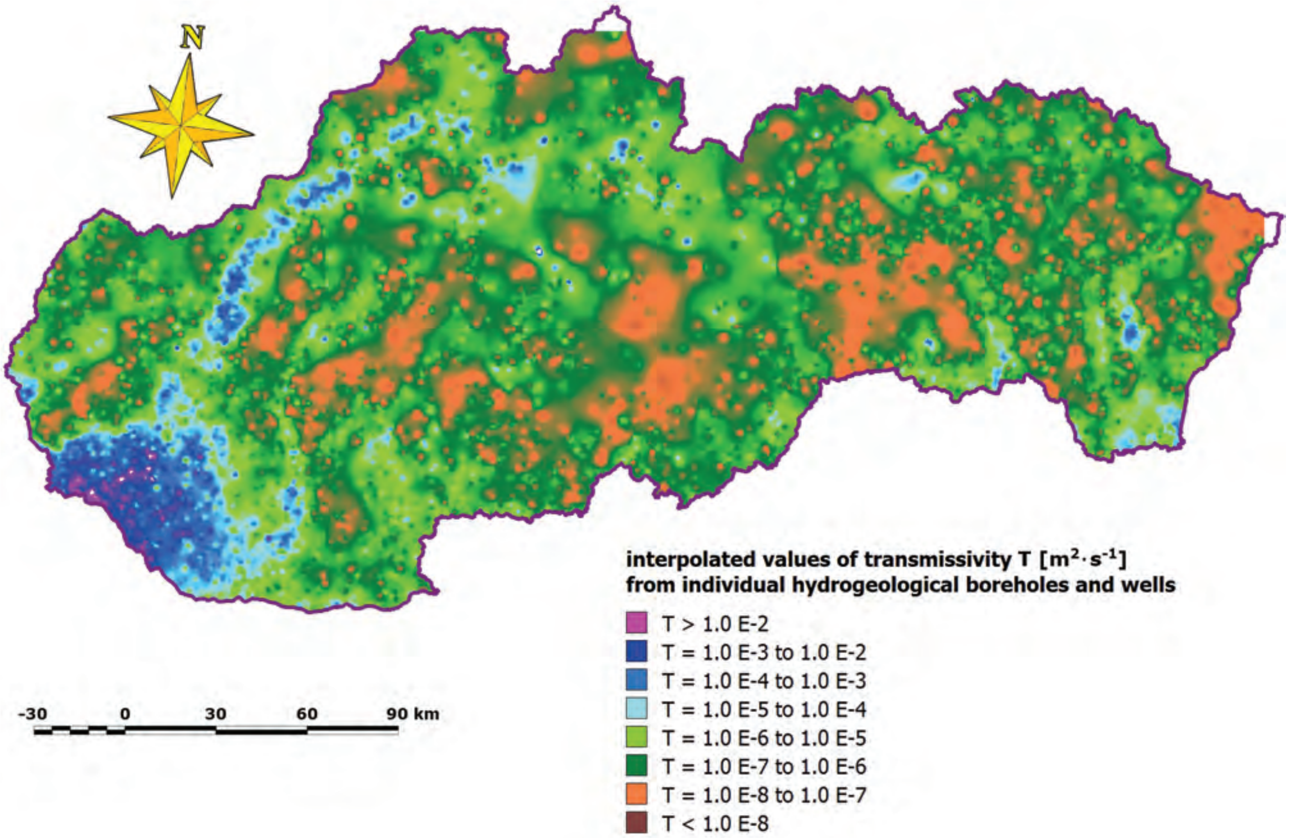


Fig. 3.19 Interpolated values of transmissivity coefficient ***T*** *set by interpretation of specific capacity from pumping tests on 16,729 individual wells and hydrogeological boreholes in Slovakia.*

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.

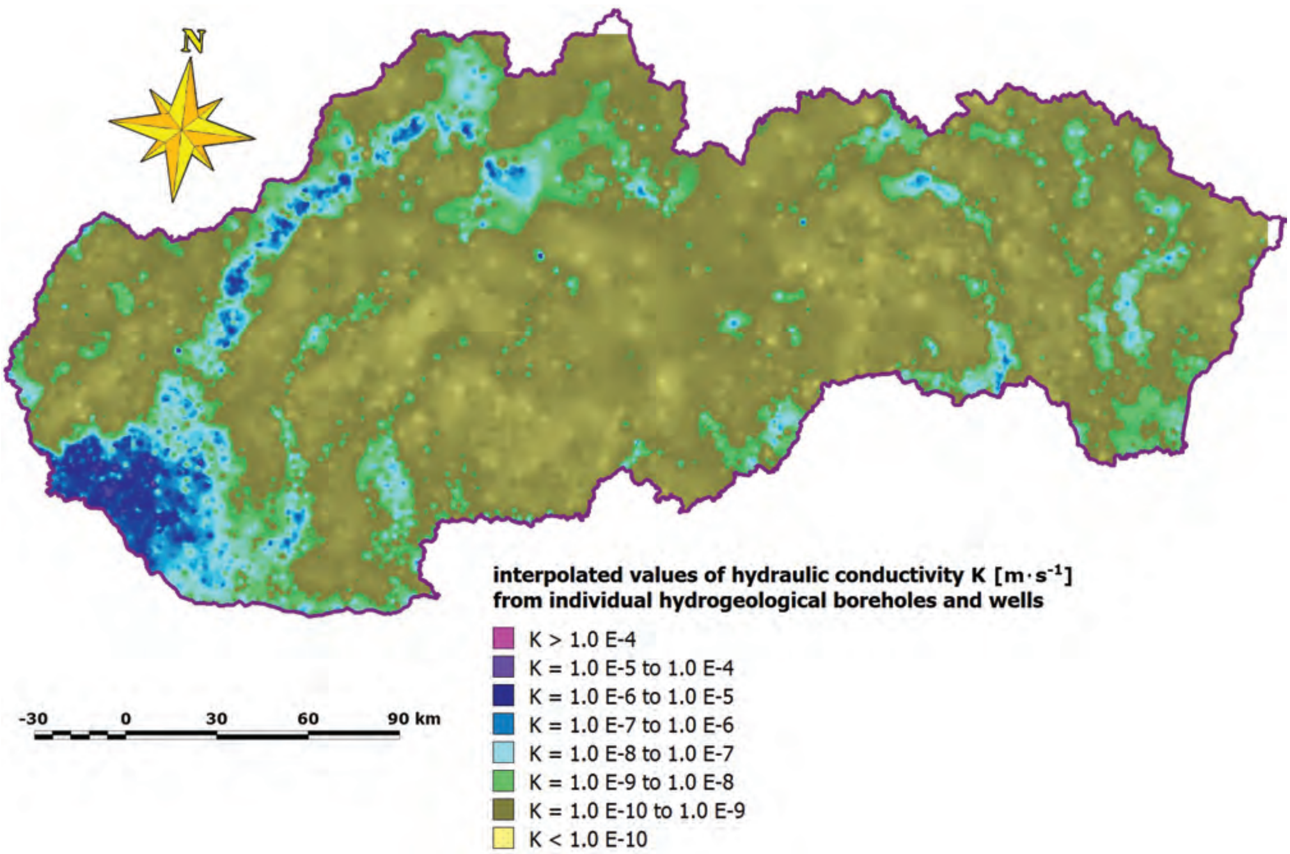


*Fig. 3.20 Interpolated values of hydraulic conductivity **K** set by interpretation of specific capacity from pumping tests on 16,729 individual wells and hydrogeological boreholes in Slovakia.*

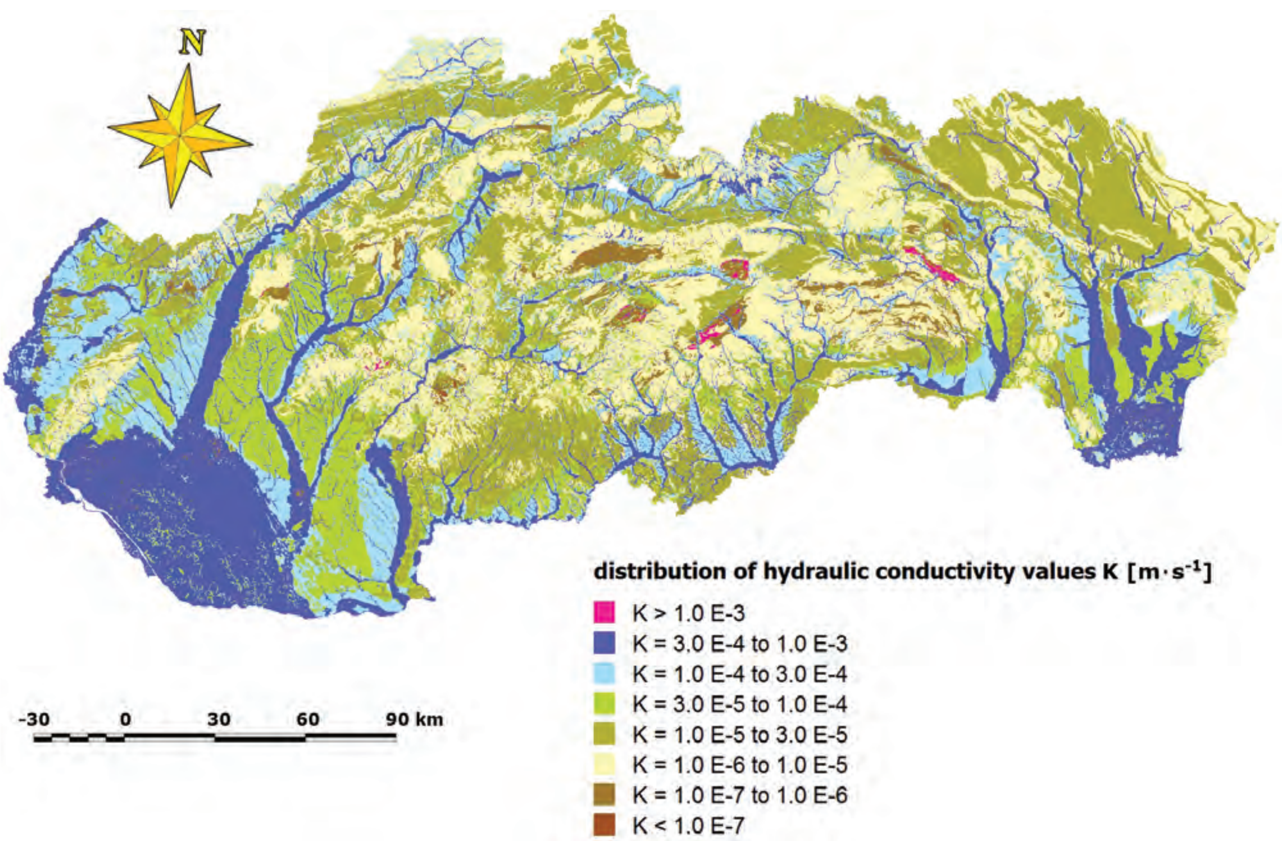


Fig. 3.21 Mean values of transmissivity set for 156 different aquifer types (31 Quaternary and 125 pre-Quaternary) delineated on the Slovak territory.

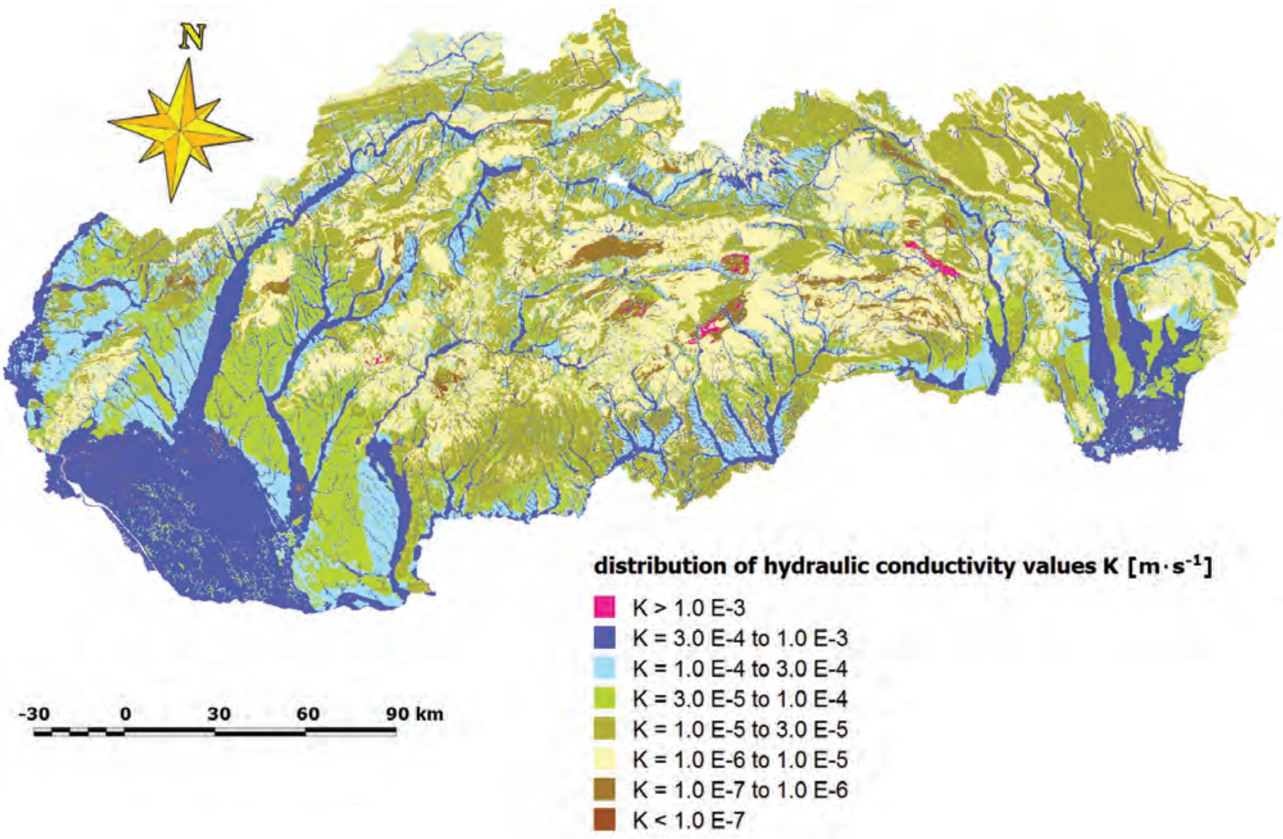


Fig. 3.22 Mean values of hydraulic conductivity set for 156 different aquifer types (31 Quaternary and 125 pre-Quaternary) delineated on the Slovak territory.

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(¹q)*** and arithmetical average ***M(¹q)*** values of specific capacity ***¹q*** 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.

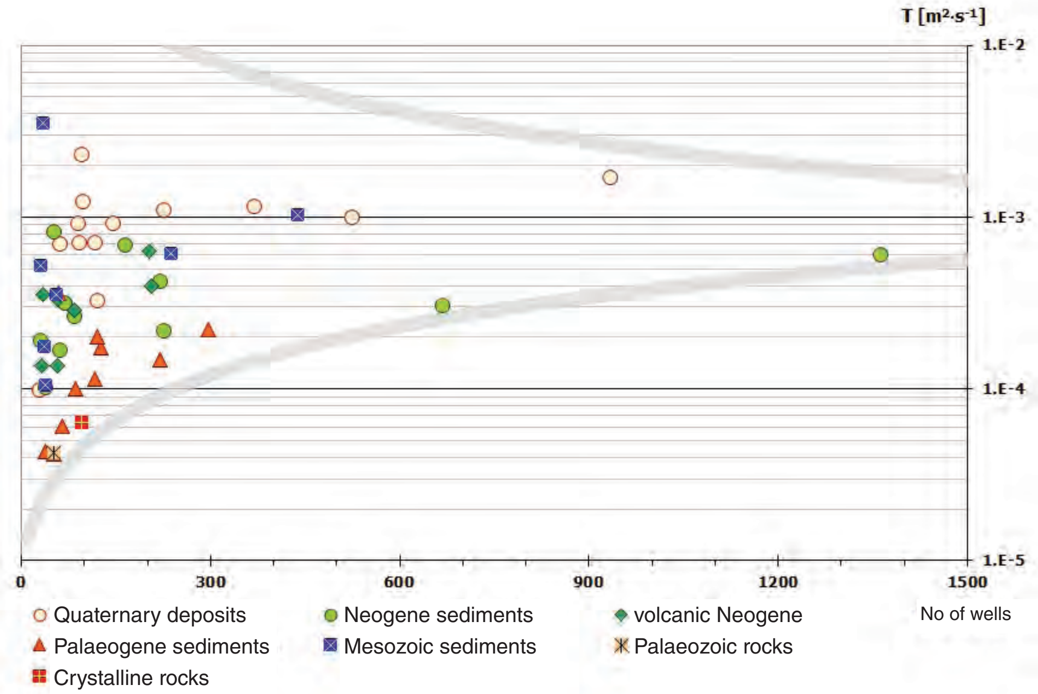


Fig. 3.23 Comparison of mean regional transmissivity values for aquifer types with ≥ 30 evaluated pumping tests on boreholes and wells.

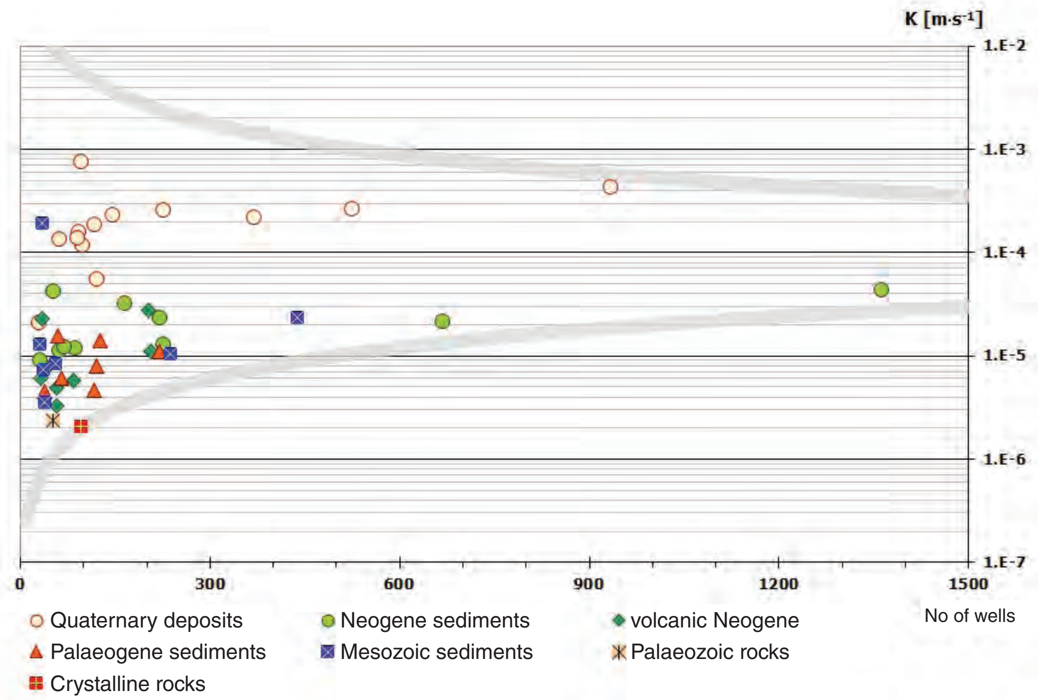


Fig. 3.24 Comparison of mean regional hydraulic conductivity values for aquifer types with ≥ 30 evaluated pumping tests on boreholes and wells.

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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