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Problems of Hydraulic Conductivity Estimation in Clayey Karst Soils

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Abstract

Even in karst areas, considerably thick soils can be found in accumulation zones. Here, the degree of groundwater vulnerability depends not only on the thickness, but also on the hydraulic conductivity and retention properties of the soil cover. The hydraulic conductivity of fine-grained karst soils from Slovakia, Croatia and Austria was studied within several international research projects, by the application of four different test methods. Results are discussed from different points of view. Triaxial tests yielded a very broad interval between the maximum and minimum hydraulic conductivity (from 5.83x10^{-7} m.s^{-1} to 3.50x10^{-11} m.s^{-1}), therefore the mean value cannot be used in any calculations. The consolidometer method gave lower values in general, between 9.40x10^{-10} m.s^{-1} to 3.59x10^{-8} m.s^{-1}. However, this method overestimates the soil "impermeability". Estimates based on grain size are unsuitable, as fine-grained soils did not fulfil the random conditions of known formula. Finally, the "*in situ*" hydraulic conductivity was measured using a Guelph permeameter. As expected, "*in situ*" tests showed 100 to 1000-times higher k_f than the laboratory tests. This method best reflects the real conditions. Therefore, only this type of data should be considered in any environmental modelling. In a soil profile, hydraulic conductivity depends on the mineral composition, depth, secondary compaction, etc. The degree and duration of saturation with water is very important for young soils containing smectite. Their hydraulic conductivity might be very low when saturated for long time, but also very high, when open desiccation cracks occur. A very slight trend was found, but only in Slovak soils, showing a decrease in the hydraulic conductivity with increasing content of the clay fraction <0.002 mm. These results should contribute to a better estimate of the protective role of soils in groundwater vulnerability maps.

1. INTRODUCTION

Karren fields are a typical karst phenomenon in the erosion zones in karst areas, where the uncovered fissured carbonate rock enables very rapid infiltration of surface water, with all pollutants included. Groundwater vulnerability is therefore extremely high. Elsewhere, there are places continuously covered with soil, which seem to function as natural pollution barriers. A considerable thickness of the soil cover can be found in depressions or in other accumulation zones. The degree of karst groundwater protection by soils depends not only on their thickness, but also on both their hydraulic conductivity and retention properties.

Between 2000–2003, soils from selected karst terrains in Slovakia, Croatia and Austria (Fig. 1) were studied within one Slovakian and three international interdisciplinary research projects. This paper summarizes one part of the results, dealing only with the hydraulic conductivity of fine-grained karst soils. It can be concluded that:

– wide intervals of hydraulic conductivity were measured by different methods in selected soil types;

– hydraulic conductivity assessment methods based solely on the grain-size distribution in the fine-grained soils are unsuitable;

– factors influencing the hydraulic conductivity are complex.

2. STUDY AREAS

Selected karst areas were chosen for investigation in all three countries. The Brezovske Karpaty Mts. (the Small

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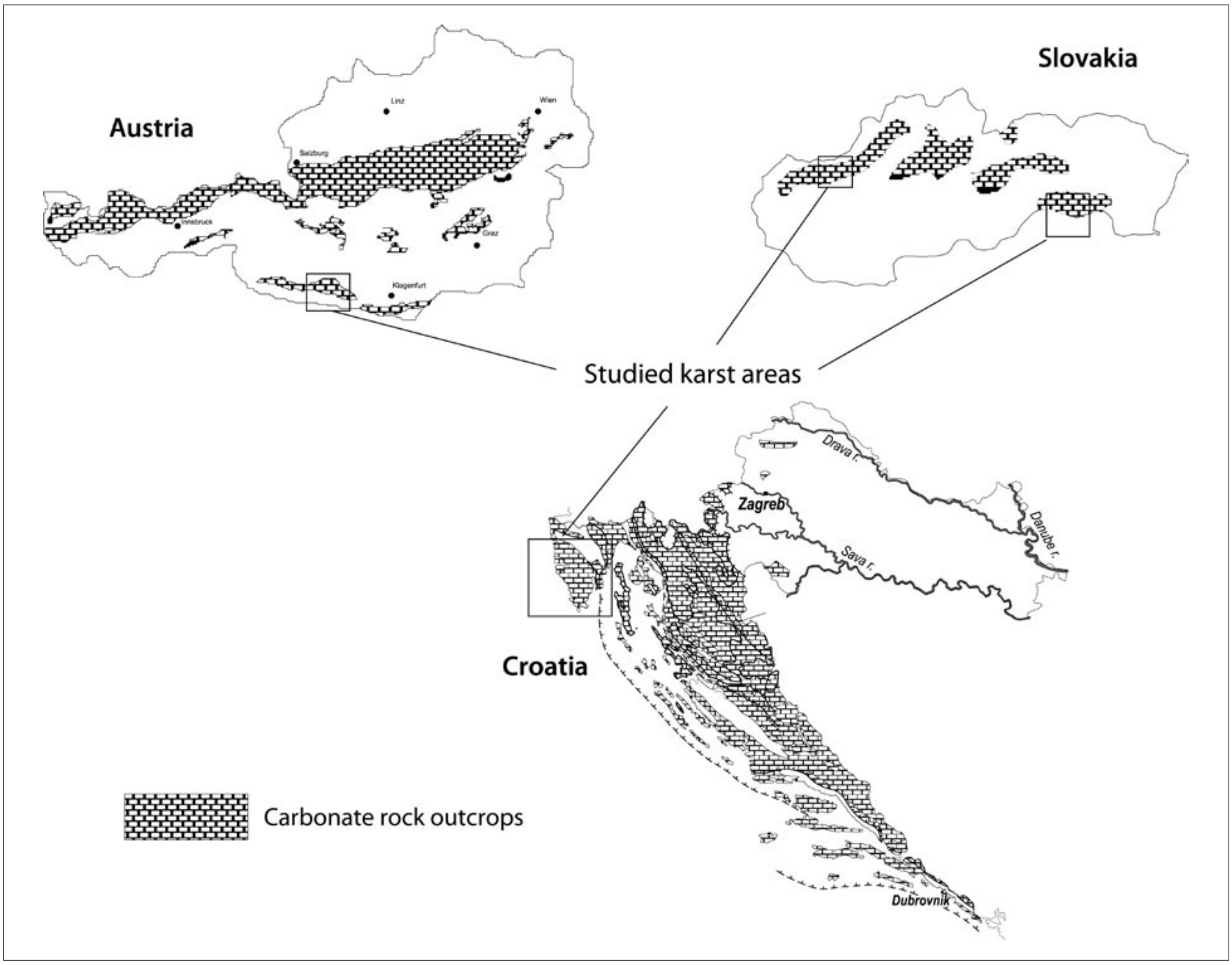

Fig. 1 Most important carbonate rock outcrops in Slovakia, Croatia and Austria and studied karst areas.

Carpathians Mts.) and the Slovensky kras Mts. (the Slovak Karst Mts.) were studied in Slovakia, the Istrian Peninsula in Croatia and the Dobratsch Mts. (the Gailtaler Alps) in Austria (Fig. 1).

Slovakia

The karst area in the Brezovske Karpaty Mts. is built up by Triassic carbonates of the Jablonica Group (Carnian Wetterstein limestones and dolomites, and Upper Carnian–Norian dolomites). They belong to the Nedzov Nappe. Both limestone and dolomite complexes of the Jablonica group are highly permeable, but the karst processes are mainly developed in limestones, producing wide karst joints, caverns and caves. The Quaternary of the Brezovske Karpaty Mts. is mainly represented by Pleistocene aeolian sediments covering the SE foot slopes of Plesiva Hora, as well as by Holocene fluvial sediments and slope sediments (BEGAN et al., 1984).

The Slovensky kras Mts. is an area with the most typical karst development in Slovakia. These exemplary karst phenomena are on the UNESCO List of World Heritage sites. The research was undertaken on the Silicka plateau. In synclinal bedding, the MiddleTriassic limestone–dolomite complex overlies the less permeable to impermeable Lower Triassic sediments that also occasionally appear on the surface. Both complexes belong to the Silica Nappe (MELLO et al., 1996). In the SW part of the Silicka plateau, the Mesozoic complexes are covered by Tertiary clays, gravels and sands of the Poltar formation. Small remnants of these sediments also occur in the eastern part of the area. Quaternary sediments are represented mostly by slope debris. Fluvial sediments are reduced to brook alluvium (MELLO et al., 1996).

Croatia

Karst terrains cover approximately 50% of Croatian territory and predominantly consist of karstified Mesozoic and Tertiary limestones and dolomites. The Istrian peninsula represents the NW part of the spacious Adriatic Carbonate Platform and consists predominantly of carbonate rocks ranging in age from Late Middle Jurassic to Eocene, with subordinate Eocene siliciclastic rocks, flysch and calcareous breccia, and Quaternary terra rossa and loess. The Istrian upper Middle Jurassic to Eocene succession can be divided into four large-scale sequences (VELIĆ et al., 1995). The 1st,

Country	**Slovakia**		**Croatia**	**Austria**
Area	the Small Carpathians Mts. W Slovakia	the Slovak Karst Mt. E Slovakia	Istria Peninsula NW Croatia	the Gailtaler Alps S Austria
Site (number of profiles)	Dobrá Voda (2)	Ardovo (1) Silica (2) Silicka Brezova (1)	Plomin (2) Medulin (2) Pekići (2)	Dobratsch (3)

Table 1 Location of sampling points (soil profiles).

2nd and 3rd of these are composed of carbonates, each terminated by important, lengthy periods of emersion, i.e. type 1 sequence boundaries (TIŠLJAR et al., 1998). The 4th large scale sequence consists of carbonate and clastic rocks and unconformably overlies the palaeorelief developed on carbonate rocks. The most widespread sediments in this sequence are flysch deposits. Since the formation of flysch, the surface has been affected by tectonics, karst processes and weathering which has led to the development of both surficial and underground features. Different types of sediments, polygenetic palaeosols and soils have been formed. For the most part, they irregularly cover all the four aforementioned large-scale sequences of Istrian carbonates and flysch.

Austria

The Dobratsch Mt. belongs to the Oberostalpin tectonic unit and is very similar to the north part of the Karavanken Mts. COLINS & NACHTMANN (1978) gave a complete description of the geology, beginning from the crystalline basement, through sedimentary rocks of Carboniferous and Permian ages, up to the Triassic complexes that prevail. The Dobratsch Mt. is mainly built up of the Wetterstein-type limestone of Ladinian age. It is up to 700 m thick, with deep open vertical fissures. These are mostly of tectonic origin, connected with the major N–S and E–W faults bordering the mountain against the valleys. The upper part of the karstic rock is typically dry, but huge and important karst springs occur at the contact with the "impermeable" Werfenian complex at the bottom, in the north, north-east and east. Due to the deep circulation along the faults, some thermal springs are also present. The summit of the mountain is built up by reef limestones (Ladinian to Carnian in age). Glacial gravelly moraines are the main Quaternary sediments, covering mostly the northern parts of the mountain with a considerable thickness. Under the steep southern slopes, huge masses of a prehistoric rockfall can be found, but the slopes are still not stable due to the active Periadriatic fault at the foot.

3. MATERIALS AND METHODS

Fifteen soil profiles at eight different locations were studied. Table 1 shows the studied sites, together with the numbers of studied soil profiles at each. Data on the pedological characteristics of the studied areas, as well as mineral composition of the soil samples have already been described in detail (ADAMCOVA et al., 2001, 2002) and will not be presented here. Both undisturbed and disturbed soil samples were taken from up to 3 horizons of every studied soil profile, depending on the soil thickness. After a macro-morphological description "on site", micro-morphological analyses of thin soil sections have been carried out. Both the qualitative and the semi-quantitative mineral compositions were studied by XRD. The soils were classified according to ISSS–ISRIC–FAO (SPAARGAREN, 1994) as Cambisols (10 profiles), Luvisols (4 profiles) and Leptosol (1 profile).

The following physical properties of the soils were tested on 38 undisturbed samples in the laboratory:

- grain size distribution: measured on the <2 mm fraction by combining wet sieving either with the hydrometer method (BS 1377 – PART 2, 1990) or with SediGraph;
- Atterberg limits and plasticity index (necessary for the engineering-geological classification): plastic limit by rolling and liquid limit by the one-point Casagrande method, both according to BS 1377 – PART 2 (1990);
- hydraulic conductivity: determined by up to 3 different laboratory methods:
  a) permeameter with a triaxial pressure chamber – method also required by soil scientists (STN 72 1020, 1990 – Method G); Austrian samples have been tested in an other permeameter type, results are incomparable – GREIFENEDER (2000);
  b) consolidometer: the filtration coefficient k_f was calculated from the consolidation curve (DANANAJ et al., 2005);
  c) calculation of k_f from the grain-size curve: applying the most suitable empirical formulas selected by the PC software GeoFil;
- in order to define the retention ability of the soils regarding heavy metals, other special laboratory tests have also been done that are not discussed here.

To complete the data on hydraulic conductivity and to check the results of laboratory tests, field "*in situ*" tests were carried out using the Guelph permeameter, but only in Slovakia and Austria (GREIFENEDER, 2000; FIALA, 1999).

Method			k_f (m.s^{-1})			
			all soils	Cambisol	Luvisol	Leptosol
Laboratory	Permeameter with triaxial pressure chamber	number of tests	30	19	9	2
		mean value	9.47x10^{-8}	8.89x10^{-8}	7.17x10^{-8}	2.60x10^{-7}
		minimum	3.50x10^{-11}	1.45x10^{-10}	1.97x10^{-10}	3.50x10^{-11}
		maximum	5.83x10^{-7}	3.97x10^{-7}	5.83x10^{-7}	5.22x10^{-7}
	Consolidometer	number of tests	33	23	8	2
		mean value	7.13x10^{-9}	6.50x10^{-9}	8.22x10^{-9}	1.00x10^{-8}
		minimum	9.40x10^{-10}	9.40x10^{-10}	1.40x10^{-9}	7.02x10^{-9}
		maximum	3.59x10^{-8}	1.73x10^{-8}	3.59x10^{-8}	1.30x10^{-8}
	GeoFil (grain size)	number of tests	40	26	12	2
		mean value	2.98x10^{-9}	2.17x10^{-9}	2.78x10^{-9}	1.56x10^{-9}
		minimum	1.01x10^{-9}	1.08x10^{-9}	1.01x10^{-9}	1.21x10^{-9}
		maximum	9.96x10^{-9}	9.96x10^{-9}	4.11x10^{-9}	1.92x10^{-9}
Field	Guelph permeameter	number of tests	51	23	22	6
		mean value	9.33x10^{-6}	8.20x10^{-6}	1.28x10^{-5}	9.67x10^{-7}
		minimum	8.09x10^{-9}	1.13x10^{-8}	5.63x10^{-8}	8.09x10^{-9}
		maximum	6.88x10^{-5}	5.49x10^{-5}	6.88x10^{-5}	2.36x10^{-6}

Table 2 Hydraulic conductivity of studied soil types – results of four test methods.

4. RESULTS AND DISCUSSION

Table 2 summarizes the hydraulic conductivity results, showing the mean, minimum and maximum values, specified by the applied method and studied soil type. The mean value of all triaxial tests is 9.47x10^{-8} m.s^{-1}, but instead of applying this number in any modelling (e.g. ZENISOVA et al., 2002; MALIK & VOJTKOVA, 2004), the very broad interval between the maximum and minimum should be remembered.

In general, lower values with smaller extremes have been measured by the consolidometer method that overestimates the soil "impermeability". The estimate from grain size produced poor results since no differences were determined between the soils, as the formulas do not include natural porosity or bulk density. Although these results are often similar to the results produced by the consolidometer, they are unacceptable, because none of the soils fulfilled the random conditions of the applied formulas (e.g. d_{10}>0.05 mm for the most frequent formula of Carman–Kozeny) (MELIORIS et al., 1986). All of the studied soils could be classified as clays in the terms of engineering-geological classification (STN 73 1001, 1987). Therefore, this computer output is not factually valid, and the method should not be applied to fine-grained soils.

As expected, "*in situ*" tests showed 100 to 1000-times higher hydraulic conductivity than the laboratory tests, reflecting the presence of big macro-pores. Such pores are usually not present in undisturbed laboratory samples. For this reason, the results of laboratory tests cannot be applied when evaluating the hydraulic conductivity of soils "*in situ*", as the differences from reality are too great.

The hydraulic conductivity of the studied soils also changes from one horizon to another within the same profile. Trends observed by one test method are often opposite to the trends seen by other methods (Fig. 2). This is because hydraulic conductivity reflects the simultaneous effect of many different factors, both primary and secondary. Grain size is only one of them.

In general, the studied Croatian soils are finer than similar soils in Slovakia which are again finer than the Austrian ones. No real correlation between grain size and hydraulic conductivity tested in the triaxial permeameter could be found. Only a very weak descending trend with the increasing content of the clay fraction (<0.002 mm) could be observed (Fig. 3), similar to the results of the consolidometer method (Fig. 4). There was no correlation between the contents of the whole fine fraction <0.063 mm and k_f (Fig. 5). A very draft estimate of the filtration coefficient k_f from the content of the clay fraction might be possible, but only for Slovak soils despite the soil type. Here, an exponential trend was found, however, the reliability is very low (Fig. 6).

The differences between the classified soil types are small. However, some differentiation can be seen looking at the results of field tests (Fig. 7). Unfortunately, there are not enough data on the Leptosols. Surprisingly, the Leptosol from Silica yielded the lowest hydraulic conductivity in the triaxial test: 3.5x10^{-11} m.s^{-1} in the uppermost horizon (depth 0–10 cm). However, this was probably due to imperfections in the method (secondary

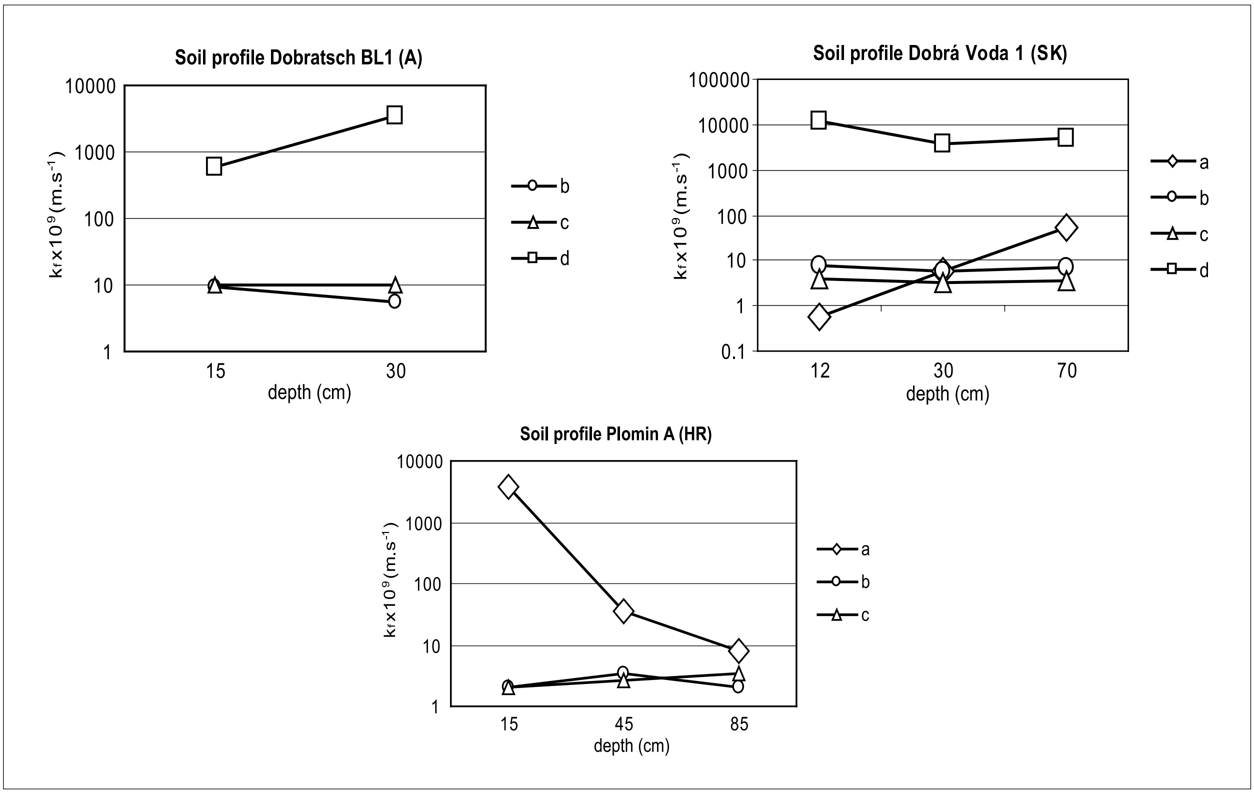

Fig. 2 Different test methods yielded partly opposing trends of hydraulic conductivity variability with depth. Legend: a – permeameter with triaxial chamber; b – consolidometer; c – GeoFil; d – Guelph field permeameter.

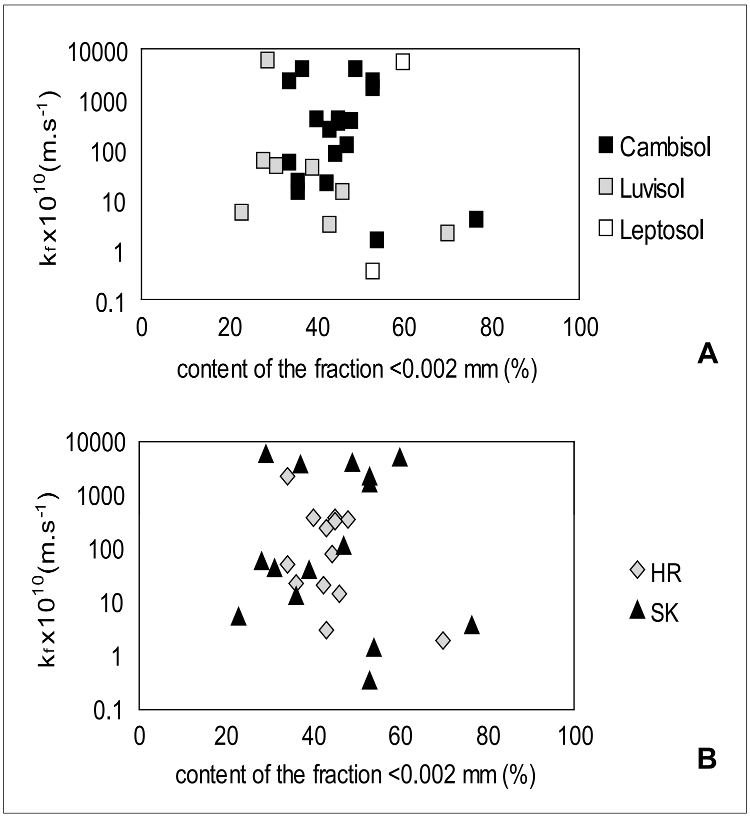

Fig. 3 Hydraulic conductivity – results of tests using the permeameter with a triaxial pressure chamber. A – distribution according to soil type; B – distribution according to country.

factor). The chamber pressure might compact the very loose sample. Also 15 cm deeper, the volume reduction after the test reached 16%. The highest hydraulic conductivity measured by this method was 5.8×10^{-7} m.s^{-1} in the upper Luvisol sample from Dobra Voda 2, probably due to many roots and cracks (primary factor) and short saturation before the test (secondary factor).

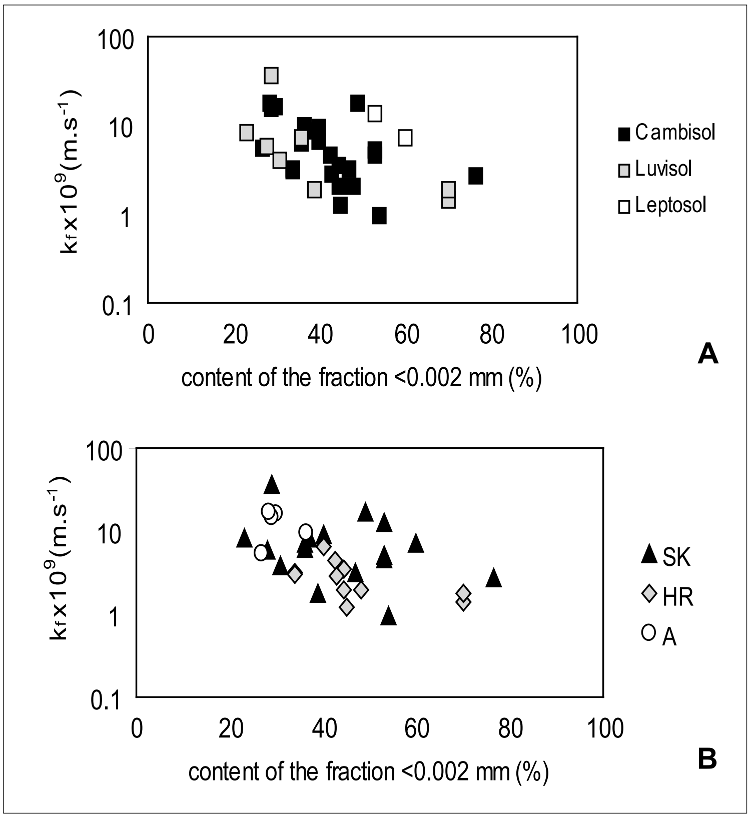

Fig. 4 Hydraulic conductivity – results of tests using the consolidometer. A – distribution according to soil type; B – distribution according to country.

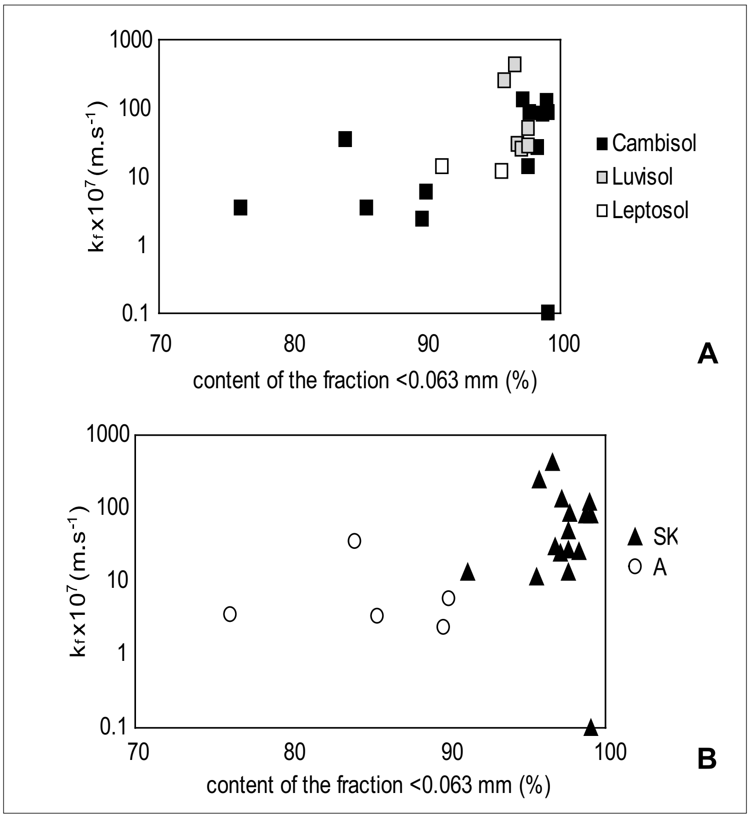

Fig. 5 Hydraulic conductivity – results of tests using the Guelph field permeameter, related to the content of the whole fine fraction (silt and clay). A – distribution according to soil type; B – distribution according to country.

Sometimes the changing k_f could be easily explained by the mineralogy, e.g. in Slovak samples containing smectite (Dobra Voda, Silica). Here, permeability decreased considerably during 2 weeks in the triaxial chamber, as the pores were closed due to smectite swelling (Fig. 8). Both the degree and duration of saturation, as well as porosity are very important, whereby these factors are in very close relationships in soils containing swelling clay minerals. There, the results of "*in situ*" tests are very season-dependent. In the autumn,

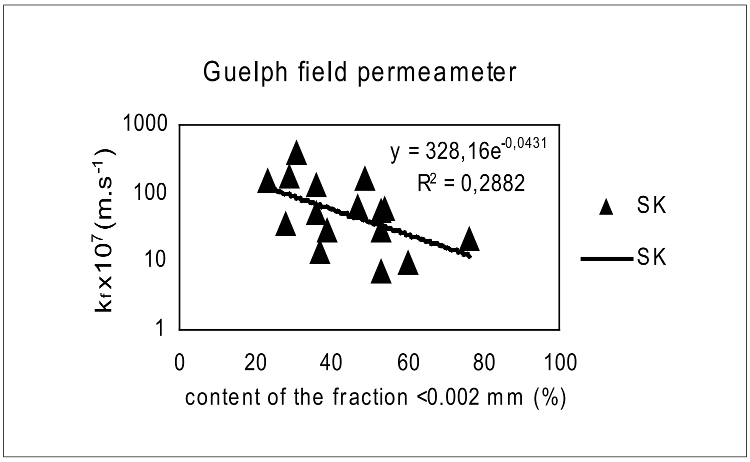

Fig. 6 Increasing content of the clay fraction should reduce the hydraulic conductivity. However, this trend could be proved only within the field tests on Slovak soils. Unfortunately, no field tests could be done at the Croatian profiles yet.

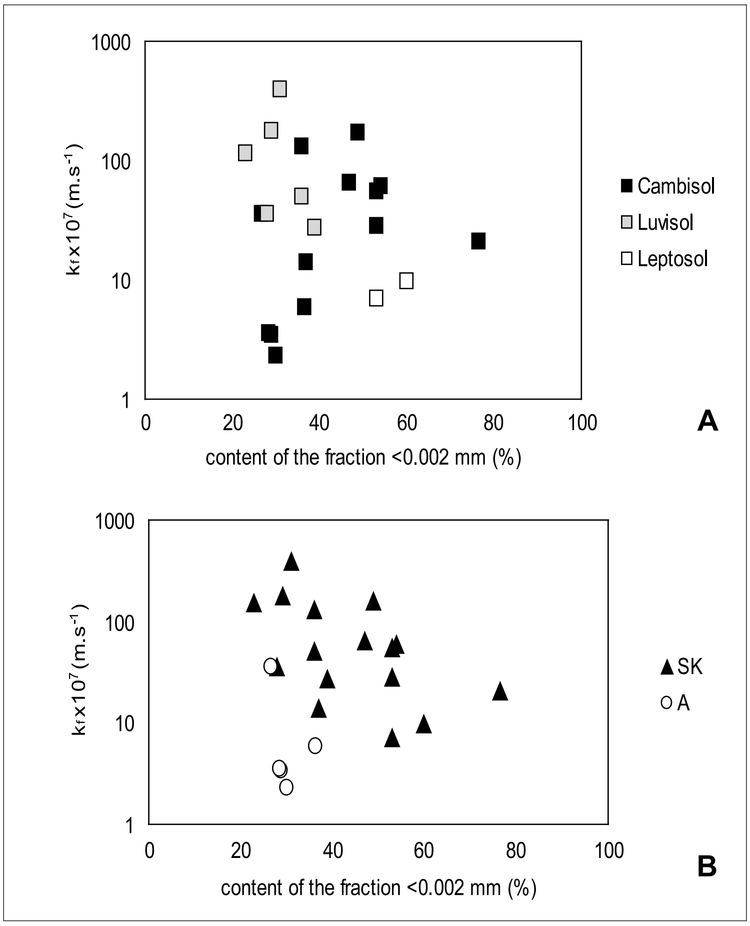

Fig. 7 Hydraulic conductivity – results of tests using the Guelph field permeameter, related to the content of the clay fraction. A – distribution according to soil type; B – distribution according to country.

when the soil was highly saturated for long periods, considerably lower hydraulic conductivity (10^{-8} m.s^{-1}) was measured in Dobra Voda than in the hot dry summer (10^{-5}–10^{-6} m.s^{-1}). This also explains the fact that Slovak Luvisols (containing smectite) seem to be slightly less permeable than Cambisols (without smectite) in the lengthy triaxial tests, having enough time for the smectite expansion, but are more permeable during the short field tests by good weather. It can be concluded that if any accident with liquid pollutants occurs on the surface covered with expandable soils (here the luvisols), the chance of successful remediation and prevention of groundwater contamination is high in the wet seasons, when the soil is saturated for long periods, but the groundwater vulnerability is very high there in dry seasons, due to the occurrence of contraction cracks.

In older soils, without smectite, secondary compaction can lower the effective porosity and thus the hydraulic conductivity. This was observed in the uppermost horizons at the Dobratsch Mt. due to cattle grazing (Figs. 9 and 10), but the primary compacting effect of the geostatic pressure was also evident in the deeper horizons of thick soils in Slovak samples.

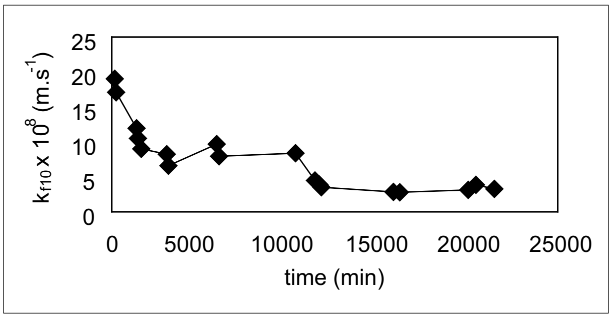

Fig. 8 Decreasing hydraulic conductivity of the soil from Dobra Voda (depth 20–30 cm), due to smectite swelling during two weeks of the triaxial test (recalculated to the temperature of 10°C).

Fig. 9 On the meadows of the Dobratsch Mt. (Austria), the hydraulic conductivity of the thin soil cover may be very low even without swelling clay minerals, being highly compacted by cattle. After the rain, water remains in flat depressions for several days.

Fig. 10 Detail from the Dobratsch Mt., showing precipitation water on the surface.

5. CONCLUSIONS

The detailed study illustrates the difficulties and the complexity of the problem of determining the hydraulic conductivity of soils. This should be taken into account when preparing a methodology for groundwater vulnerability mapping (MALIK & SVASTA, 1999; MARSCHALKO & IDES, 2000). Some attempts have already been published, where the assessment of soil permeability was based solely on an field estimate of the content of the clay fraction. But, such results are far away from the hydraulic conductivity measured "*in situ*". Therefore, the methodology needs further development, based on results collected from many field tests and maybe sorted according to the exact soil type in terms of soil science (the weather conditions during the test period should be also taken into account). This would allow soil maps to be used as an important input for groundwater vulnerability mapping.

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