CHARLES UNIVERSITY IN PRAGUE
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FLOW AND MEAN RESIDENCE TIME IN KARST UNSATURATED ZONE (OCHOZ CAVE, MORAVIAN KARST)

Summary of PhD. thesis
by
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1. INTRODUCTION

Mean residence time of water in the underground is an essential hydrogeological parameter and its knowledge has functional applications in the field of groundwater use and protection. It may help to predict future evolution of groundwater contaminants or to asses protection limits, especially in karst environment, where quantification of pollution and groundwater flow prediction is difficult due to its heterogeneity.

Flow pattern, mean residence time and geochemical processes in karst unsaturated zone and epikarst are intensively studied nowadays (Kogovšek 2010, Perrin et al. 2003, Aquilina et al. 2005, Tooth and Fairchild 2003). Karst unsaturated zone plays a fundamental role in karst aquifer and caves protection against contamination of anthropogenetic origin (Mali 2006, Zuber a Motyka 1998, Mudry et al. 2003). Considerable water volume can be stored in unsaturated zone (Perrin et al. 2003) and after intensive rain events, direct outflow from unsaturated zone can represent a fundamental part of spring yield, nearly 50 - 70 % (Lee and Krothe 2001, Trček et al 2006, Aquilina et al. 2005). Geochemical processes in unsaturated zone influence water composition (Field 1999, Fairchild 2000, Tooth and Fairchild 2003). Disolution of $CaCO_3$ is essential in soil and epikarst. Its deposition in the cave speleothems is influenced by processes in unsaturated zone and flow distribution among particular sites and its trace is recorded as an isotopical signal of ^{18}O and ^{13}C in speleothems, which is an important paleoclimatic indicator (Baldini et al. 2006, McDermott et al. 2005, McDonald et al. 2007).

Unsaturated zone in karst represents complicated, hydrogeologicaly heterogennous and anizotropic environment, where mean residence time cannot be simply determined from hydraulic parameters, moreover we do not know the flow geometry.

Various studies devoted to mean residence time in karst unsaturated zone differ in their results. Mean residence time vary from weeks (Harmon 1979) and months (Atkinson 1985, Fuller et al. 2008, Lambert a Aharon 2008) to years or decades (Kluge et al. 2010, Even et al. 1986). Several authors found stable $\delta^{18}O$ signal, which indicates values of mean residence time higher than 1 year, even in shallow parts of unsaturated zone (Yonge et al.1985, Cabalero et al 1996, Trček 2003). It is not clear with which part of karst the longest residence time can be connected. Perrin (2003) and Aquilina et al. (2005) suggest, it doesn´t have to be necessarily in saturated zone, that have been generally supposed, if already soil and epikarst can cause residence time over 1 year.

The aim of my thesis was:

- to study groundwater flow and residence time in unsaturated zone and epikarst above the Ochoz cave in the Moravian Karst
- to compare residence time in unsaturated zone with residence time in saturated zone
- to distinguish the role of soil cover and determine residence time in soil
- evaluate what part consist of freshly infitlrated water during intensive rain events
- to describe flow and conductivity course at automatically long-term monitored dripping site E in the Ochoz cave
- to asses limestone storativity from groundwater level oscillation in the boreholes and look into its relation with depth
- to try to create a conceptual model of unsaturated zone convenient for results

In the Czech Republic this topic hasn´t been studied much until now (Bruthans et al. 2004, Bruthans 2006). Studied site represents an unique underground laboratory. It has been investigated by J. Himmel from 1987, who equiped a representative dripping site „E“ with an automatic meassuring station, which collects water from unsaturated zone with no contact with cave atmosphere. It enables to observe precipitation leaking into the soil cover above the cave as an input of the system on one hand and percolation in the cave as an output on another hand. Most of studies deal with water that is simply dripping from the cave ceiling which is not representative due to reactions with cave atmosphere. Moreover this locality has a large potential to use many methods like environmenal tracers investigation, tracer tests through unsaturated zone, monitoring of δ ^{18}O record after snowmelt or monitoring of soil water chemical and physical parameters, etc. Study comprises sampling and analyses from 2004 – 2008. It follows the work of Bruthans and Zeman (Bruthans 2004, Bruthans et al. 2006) who started with oxygen and tritium isotopes research of unsaturated zone in karst regions in the Czech republic in 2001 and long - term observation of Himmel (1993).

Figure 1. Location of studied area in the map of the Czech republic.

2. STUDY SITES

Study area is situated in the Moravian Karst, which is the largest (92 km^2) and the most developed karst area in the Czech Republic. About 1133 caves are registered here (Hromas et al. 2009). Karstification is connected to limestones of devonian age (Macocha formation, Vilémovice limestones), high grade, folded and well lithified but not metamorphosed.

Carbonates of Macocha formation create the main hydrogeological structure. Permeability is of karst-fissure character. Boreholes and tracer tests proved flow even deep in the freatic zone, under level of the erosion base. Dotation of karst aquifers proceeds from precipitation and sinking surface streams.

Karst unsaturated zone is in general several tens to more than 100 m thick, saturated zone of karst aquifer reaches up to 500 m. Base of unsaturated zone is easily accessible in many caves thanks to the existence of large amount of subhorizontal cave passages.

The main site of interest – the Ochoz cave is situated in the southern part of the Moravian Karst. The altitude ranges between 320 – 400 m a. s.l. The climate is moderate with mean annual temperature 8,4 ^{0}C Average annual precipitation is about 628 mm in close Hostěnice vilage

(Himmel 2002). Thickness of unsaturated zone ranges from 10 to 70 meters here. Soil cover formed by rendzins is between 10 – 100 centimeters thick. Terrain above the cave is covered with mixed forest (oak, hornbeam and ash-tree prevail). Surface above the cave has never been cultivated. There were three principal seepage sites observed in the Ochoz cave: E, Kužel and Beránek. They differ in the flow and its regime through the year. E can reach cca 50 l/h in its maximum, its part called E2 is active all the year, Beránek flows only after intensive rains or snowmelting (its discharge doesn´t get across 10.2 l/h in its maximum) and Kužel is less intensive (up to 2.4 l) but has relatively stable year-long flow.

Reference localities Rudické propadání, Býčí skála and Amatérská caves are placed in the nothern part of the Moravian Karst. All are large cave systems (Amatérská Cave is the longest one in the Czech Republic, 32 km) with an active underground stream. At least some parts of the surface above them used to be cultivated in the past. The thickness of unsaturated zone above the studied site in Býčí skála cave reaches 60 - 100 m and about 150 m in Rudické propadání. An intensive seepage site Mapa republiky is placed in Býčí skála, it is active all the year as well as Kašna seepage site in Rudické propadání (about 0.2 – 0.5 l/h in average).
Among objects sampled for comparison as objects predicative of saturated zone, following karst autochtonnous outlets were studied: PB337 – Kaprálka (in the valley of the Ochoz cave, 1 km far from the cave entrance), Konstantní přítok in Amatérská jeskyně and Stará řeka in Rudické propadání cave.

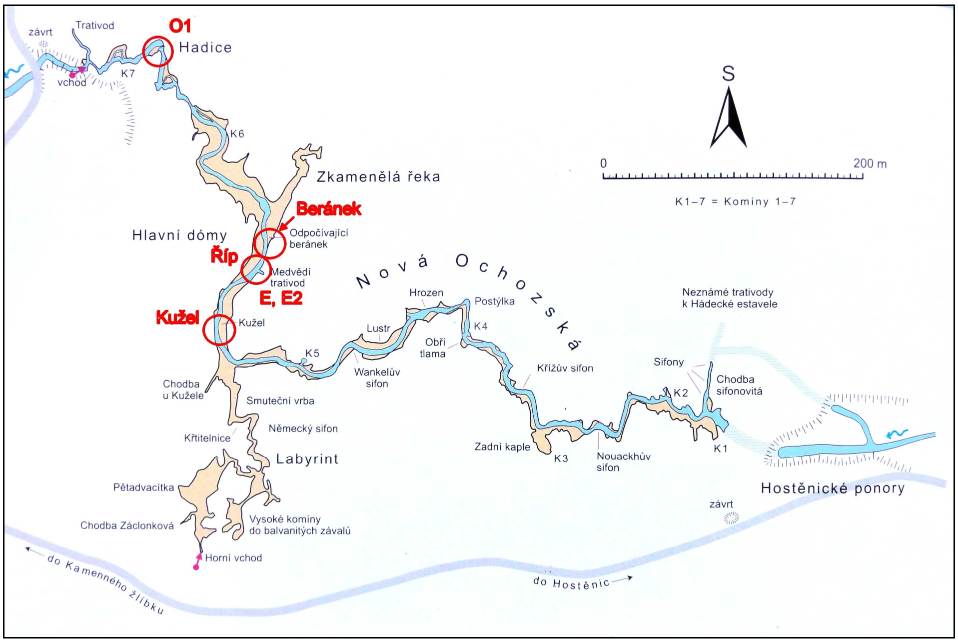

Figure 2. Map of the Ochoz cave with studied seepage sites E, Kužel, Říp, Beránek and O1. (Hromas et al. 2009)

3. METHODS

3.1 Measurements of flow rate, temperature, pH and conductivity of water, sampling

I measured discharge/water volume, temperature, pH and conductivity (Cond 340i, pH 330i WTW Co.) and took samples of seepage and soil water on monthly basis. Sampling for $\delta^{18}O$ content and chemical composition was performed monthly, sampling for tritium, CFC and SF_6 concentration was done occasionaly several times per monitoring period.

During snowmelt or rain events the frequency was higher. For cases of intensive flow events an automatic programmable sampler ZKZ 1.0 was developed (cooperation of O. Zeman and J. Kukačka from The Charles University in Prague with I. Záruba from Narex SAT, Ltd. company). Sampler allowed to cover even short - time changes during seepage water outbreak when the cave wasn´t accessible due to flood, etc.

3.2 Soil Moisture determination
Soil samples for moisture determination (by drying) were taken monthly above the Ochoz cave

3.3 Suction pressure measuring
Five tensiometers with different depth ranges (0.4 – 0.9 m below surface) were located in the soil to survey the stage of soil saturation, when the water can freely flow down by gravitation.

3.4 CO_2 partial pressure measurement
Partial pressure of carbon dioxide in the soil atmosphere was manually monitored with Anagas CD 98 (Environmental Instruments)

3.5 Flow through the soil cover
- Together 7 gravitational (no tension) lysimeters were placed into the soil cover above the cave, to the depth of 0, 15 and 60 cm below the surface (further signed L0, L15 and L60). L0 represents water that infiltrates into the soil cover through leaves and other organic material; L15 correspond to water leaking through thin soil cover, like above the seepage site E. L60 lysimeter is placed on the soil base. It is situated on a place with higher soil cover thickness than above seepage site, so its parameters enable assess trends under thicker soil layer. Volume of infiltrated water, its pH, conductivity and temperature were meassured and samples for water chemism and $\delta^{18}O$ analysis were taken with the interval of 1 month.

Continuous automatic logging of inflows into L15 lysimeter

Lysimeter L15 was equipped with a data logger and a sensor for monitoring the level and temperature of water that had infiltrated into the soil with the interval of 1 hour. This information enables to determine the delay between rain infiltration into the soil and hydraulic reaction of seepage.

3.6 Precipitation monitoring and sampling
Precipitation amount was observed daily in the close Hostěnice village, samples for $\delta^{18}O$ analysis were taken (mixed weighted monthly sample).

3.2 Continuous automatic data logging in the cave
On seepage site E, where seepage water is collected with no contact with the cave athmosphere, there was an automatical gauge for discharge, conductivity and temperature of water with a measuring step of 20 minutes.

3.8 Analysis and data processing
Chemistry analysis were accomplished at ALS Group (former Ecochem) laboratories.
Content of CFC (11- $CFCl_3$, 12- CF_2Cl_2, 113- $C_2H_2F_3Cl_3$) and SF_6 in water was meassured by H. Oster with gass chromatography in GC – ECD Spurenstoff laborator. Tritium activity was measured at liquid scintillation spectrometer Tri Carb 3170Tr/Sl (Canberra – Packard Company) after electrolytic enrichment 1:10, at the Charles University (Z. Churáčková). F. Buzek gauged values of δ18O (H2O) at mass spectrometer Mat Finnigan 251 at laboratory of

the Czech Geological Survey (equlibration with CO2), values of δ2H were determined at mass spectrometer Delta Plus at Brigham Young University in USA (J. Bruthans). Accuracy is ± 0,15 ‰. Values of $\delta^{18}O$ a $\delta^{2}H$ are related to SMOW (Hladíková 1988). For CO_2 equilibrium in water calculations I used PHREEQC-2 code (Apello and Postma)

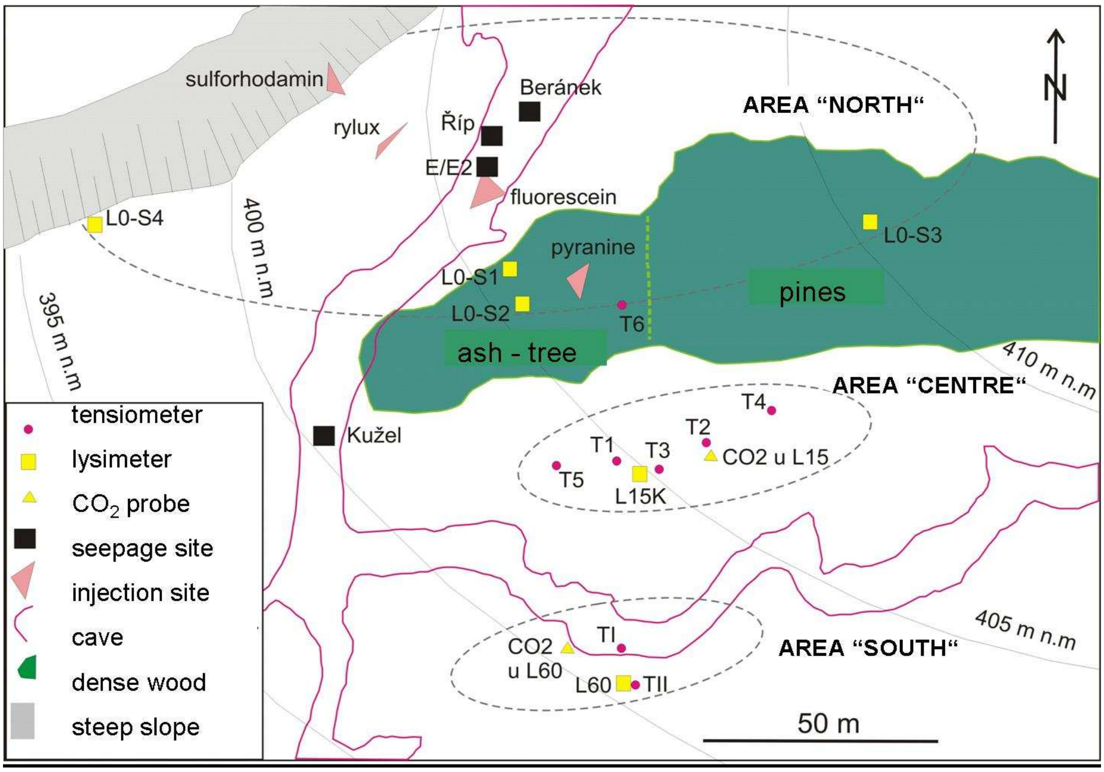

Figure 3. Groundplan of the Ochoz cave with localization of seepage sites and lysimeters, tensiometers and CO_2 probes on the surface above

FLOW PC program (Maloszewski and Zuber 1996) was used for mean residence time modeling based on tritium, oxygen and CFC. The best fit between precipitation and seepage $\delta^{18}O$ content is sought by trial – error method. The user chooses potential residence time and proper model type. I used piston flow model, dispersion model, exponential model and combination of piston flow with exponential model.
Storativity was calculated using method of Atkinson (1977) from water level oscillation in boreholes (Mokrá quarry in the vicinity) compared to outflow from the system (PB0337 Kaprálka spring) during flow recession periods.

4. RESULTS AND CONCLUSION

4.1 Mean residence time

By means of environmental tracers (^{3}H, ^{18}O, CFC a SF_6) I determined mean residence time in unsaturated zone above the Ochoz cave in the Moravian Karst (seepage sites E, Kužel and Beránek and lysimeters 15 and 60 deep in the soil). Besides the Ochoz cave area I set mean residence time at seepage site Kašna in the Rudické propadání cave and seepage site Mapa republiky in the Býčí skála cave. Also objects representing saturated zone were studied for comparison – autochtonnous karst outlets: PB0337 – Kaprálka (in the vicinity of the Ochoz cave), Stará řeka (Rudickém propadání) and Konstantní přítok (Amatérská jeskyně).

Mean residence time is following:

Unsaturated zone

the Ochoz cave : seepage site E: 8-13 years (based on tritium), 8-15 years (based on SF6) and 8-20 years (based on CFC12),
seepage site Kužel: 14-17 years (tritium)
seepage site Beránek: 7-15 years (tritium)
- Rudické propadání: seepage site Kašna: 18-20 years (tritium)
- Býčí skála: seepage site Mapa Republiky: 150 years (tritium).

Mean residence time at studied sites in unsaturated zone of the Moravian karst reaches 7 – 20 years. Extremly long residence time at Mapa republiky seepage site is caused by specific geological setting.

Saturated zone

- spring PB0337 (Kaprálka): 11-20 years (CFC)
- Amatérská jeskyně, Konstantní přítok: 16-20 years(tritium), 10-20 (CFC 113) and 5-12 (SF_6)
- Rudické propadání, Stará řeka: 12-17 years (tritium), 12-23 years (CFC113) a 9-17 years (SF6)

Generally mean residence time 5 – 23 years was found in autochtonnous karst outlets

Residence time in saturated + unsaturated zone (in karst outlets) is not in any large contrast to residence time in unsaturated zone only (seepage water). It means that water that infiltrated into unsaturated zone doesn´t have to stay for longer time in saturated zone to reach total residence time at the outlet. This conclusion contributes to the hypothesis that the main water storage may be situated in unsaturated zone, above the regional water level in the Moravian Karst. Considering epikarst to be a principal contributor to total groundwater storage corresponds with conclusions of other studies (Perrin et al. 2003, Aquilina et al. 2005a, Mudry et al. 2008)

– mean residence time in soil is 3 – 6 months in the depth of 60 cm, based on $\delta^{18}O$ (H_2O), it didn´t get over 8 months, 10 cm deep in soil it is shorter than 1 months

For comparison, water molecules spend 7 -20 years in lower parts of unsaturated zone and few months in the soil only. Piston flow acts in the soil. Seasonal variability of $\delta^{18}O$ values is evident in the soil cover. It diminishes with depth, but can be still observed 60 cm below the surface.

- objects sampled both for tritium and for CFC and SF_6 (E, Konstantní přítok and Stará řeka) provided similar result, what showed that used environmental tracers are suitable for conditions of the Moravian karst area

4.2 Isotopic composition of of seepage water

– based on tritium activities- flow components that had infiltrated after 1950 are present in unsaturated zone. Only at Mapa republiky seepage site, an essential part of water can be from the period before 1950. Higher tritium activity at Kašna and Kužel seepages can mean more water from 60 – 70ies. Water that has infiltrated during last 20 years prevail.

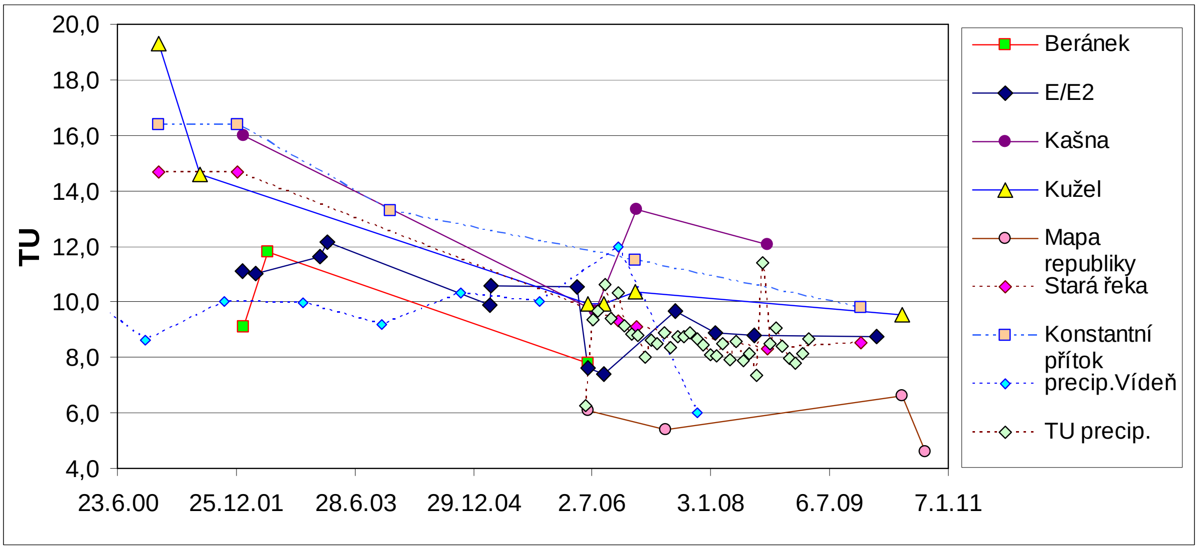

Figure 4. Tritium content in seepage water and precipitation. Data until 2005 are from Bruthans (2006). “Precip. Víděň“ is a longterm mean weighted record from Vienna monitoring station, “TU precip.“ is from Uhlířská study site in the Jizerské mountains (M. Šanda, unpublished data)

– $\delta^{18}O$ (H_2O) has a dampened signal in time, there is no sign of seasonality in comparison with precipitation
Individual seepeage sites have similar $\delta^{18}O$ content, and so similar part of flow component with short residence time

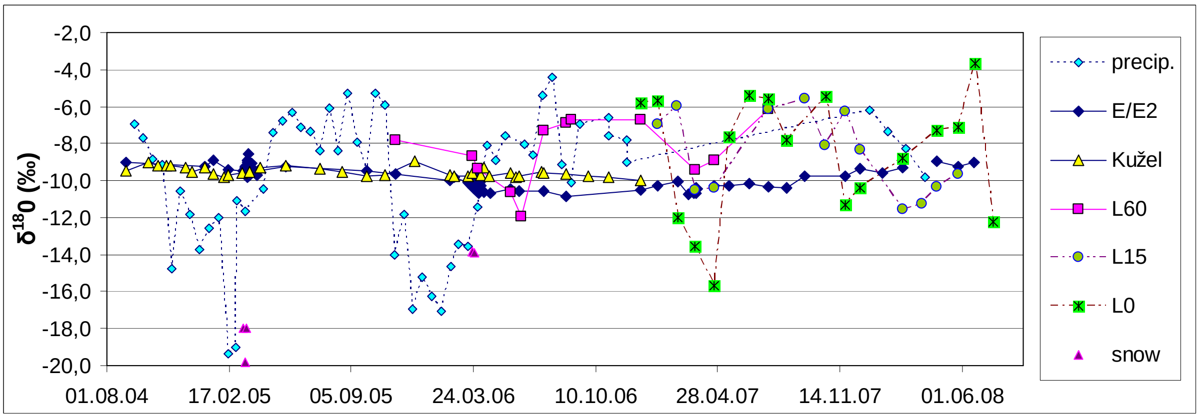

Figure 5. Signal of $\delta^{18}O$ in precipitation, soil and seepage water and snow.

4.3 Suction pressure, soil moisture, flow in soil and seepage activity reaction

- Soil moisture above the Ochoz cave ranges between 20 to 40 mass %. Moisture value doesn´t decrease below 20 mass % even in dry period.

- Suction pressure monitoring showed that water could flow downward in the soil layer mainly in winter period (December 2006 to March 2007). Besides this time water suction into small voids can be expected, with the exception for bypas flow. Percolation even in summer was possible in places with soil rich in clay sediments. This was documented also with isotopical composition of water infiltrated in L60 lyzimeter corresponding to summer precipitation (-7 to -9 ‰ δ^{18}O).

- volume of water percolating down through the soil has no correlation with activity of seepage sites, primarily a storage in soil and weathered rock in unsaturated zone is filled (approximately 50 mm of water column) and after water gets into perched aquifer in epikarst and seepage flowrate starts to increase. It declares that epikarst reservoir is not completely filled with water, it it was – level rise in the soil would be accompanied with increase of seepage flowrate

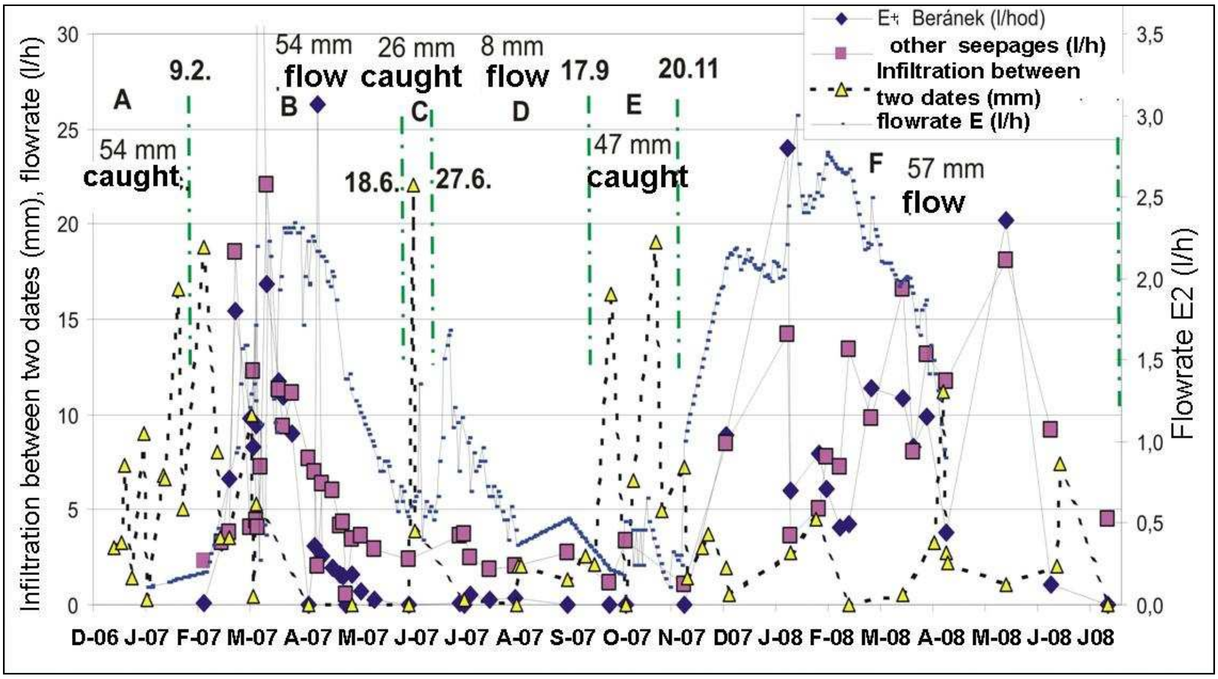

Figure 6. Relation of infiltration into the soil and seepage flowrate. For the first time, water percolates down via soil and seepage sites do not react (period A and E), after infiltration of cca 50 mm of water column (54 in period A and 47 mm in E), seepage activity appears.

4.4 CO_2 concentrations in the soil atmosphere

- CO_2 concentrations in the soil atmosphere above the Ochoz cave have an average value 0,5 %, which is common for the Moravian Karst region. No seasonal trend was observed. Soil CO_2 concentrations rise with depth and based on PHREEQC evaluation it can increase up to 5 % in the lower part in the unsaturated zone (seepage E)

4.5 Flow during intensive rain and snowmelt events, conductivity and δ18O signal

– Measurement of conductivity, flow rate and $\delta^{18}O$ composition during high flow events connected to snowmelting in 2005 and 2006 declared previous results of (Bruthans 2006), that even during extreme water stages, freshly infiltrated water doesn´t compose more than 20 %. Pre-event water is pushed out from the epikarst. Seepage $\delta^{18}O$ composition was not significantly influenced with very different $\delta^{18}O$ composition of snow. As well conductivity value was not influenced more than in size of 5 % in 2005, resp. 8 % in 2006.

– Hydraulic impulse spreads tens of hours or first days. It is very fast compared to long residence time.

– Unsaturated zone represents a huge reservoir. Unlike from intensive hydraulic reaction, $\delta^{18}O$ and conductivity values, chemical composition don´t vary significantly in time at the drainage from the epikarst. In contrast, there is a high variability in the soil. This refers to huge epikarst capacity.

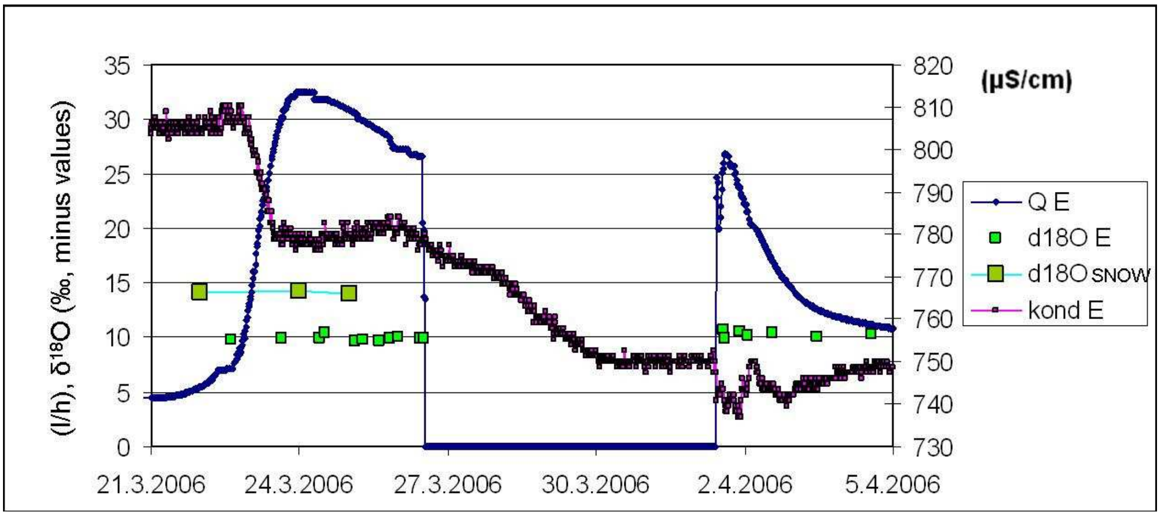

Figure 7. Flowrate, conductivity and $\delta^{18}O$ content at seepage site E in the Ochoz cave during snowmelt 2006. Different $\delta^{18}O$ snow composition is evident. Sharp flowrate decline was caused by technical trouble at monitoring station.

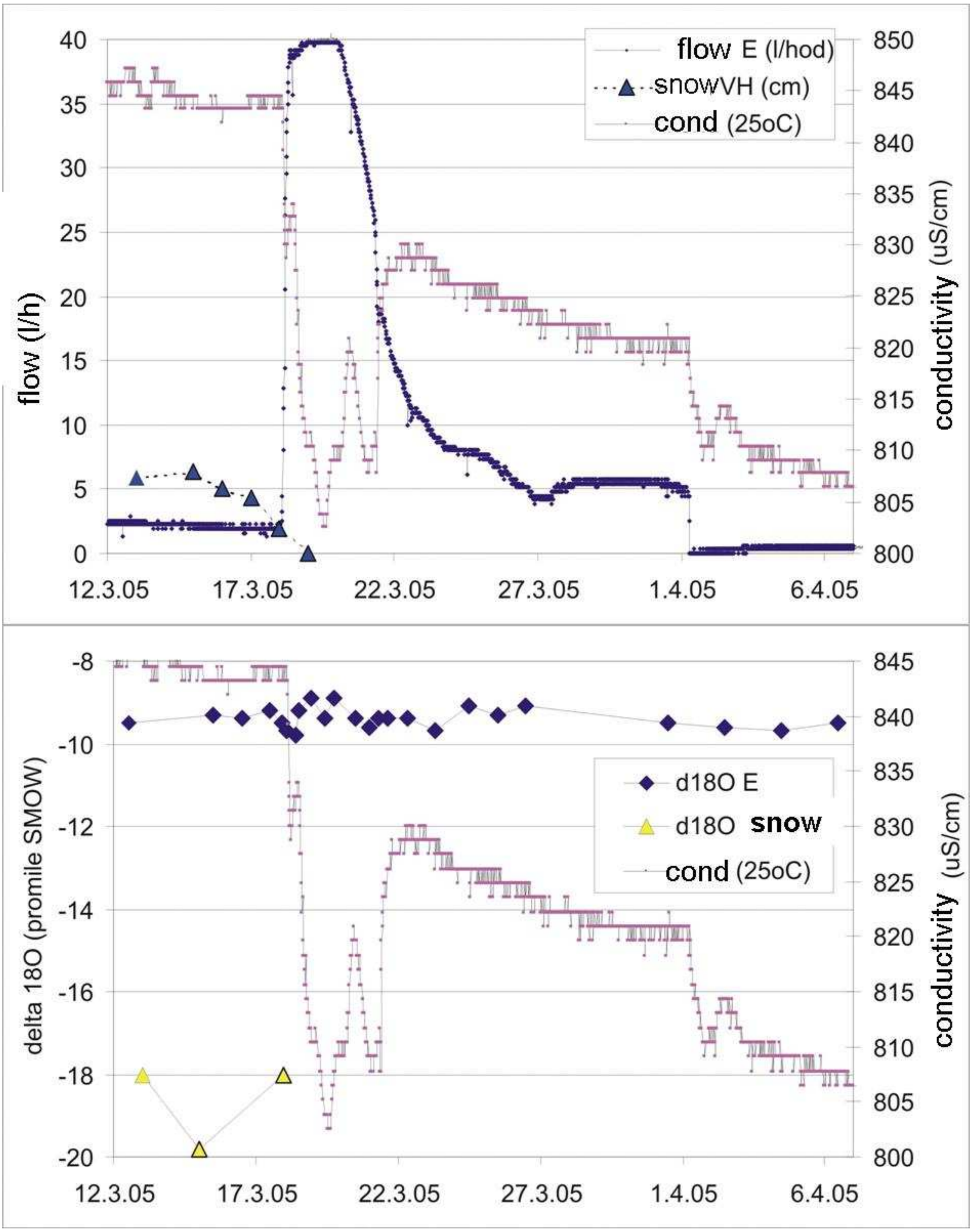

Figure 7. Snowmelt in 2005 at seepage site E in the Ochoz cave: seepage discharge increased (20x), conductivity decrease was in 5 % only.

4.6 Storativity

– Storativity was determined from parallel water level recession in boreholes in unsaturated zone and flowrate decrease of a local spring. Its value depth is 0,6-0,8 % (close to 10 m b.s.) and declines with depth to 0,3 % (100 m b.s.). There isn´t any sharp boundary between unsaturated and saturated zone. Epikarst can´t be separated from the rest of unsaturated zone in the Moravian Karst.

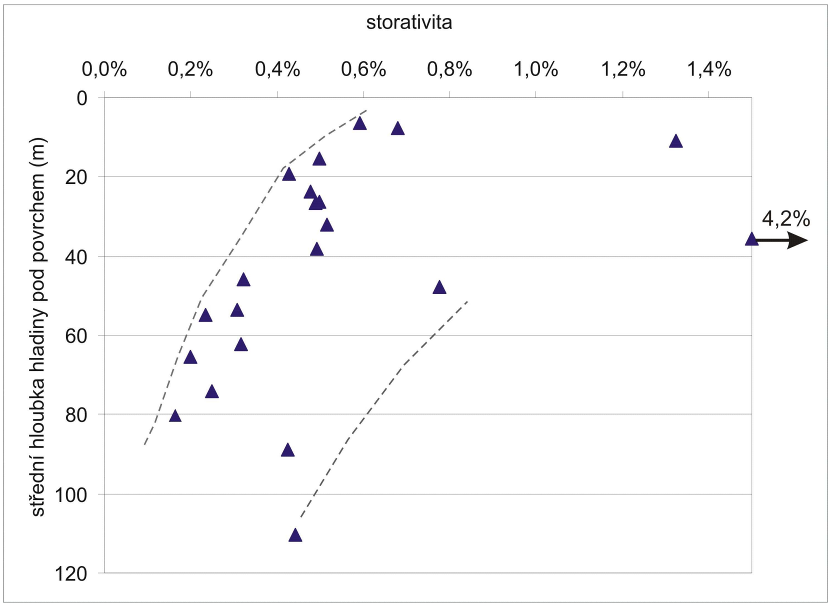

Figure 8. Storativity and depth below the ground

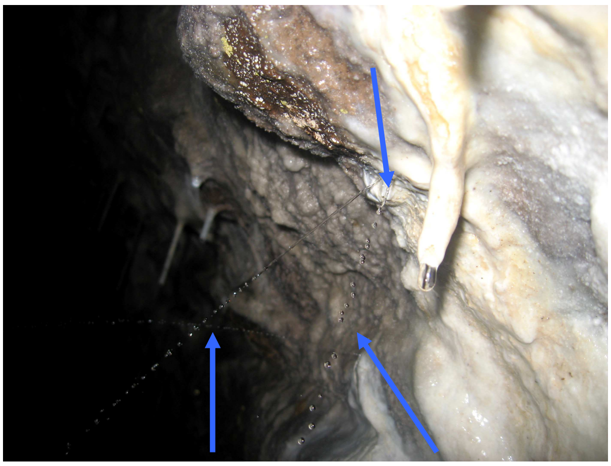
Figure 9. Water jetting out (under pressure) from the cave wall (from perched aquifer above the cave ceiling) during high flow stage

4.8 Conceptual model of flow in unsaturated zone

Based on longterm observation a conceptual model of flow in unsaturated zone was created. It consists of 4 reservoirs: soil, epikarst, lower part of unsaturated zone and perched aquifer above the cave ceiling. Regime of flow, water mixing and flow paths distribution depends on epikarst saturation and intensity of infiltration.
Obviously the main water storage in epikarst is placed in lower part of unsaturated zone in corrosively widened fissures. Flow capacity of fissures is limited, thus with high saturation water starts to accumulate here. Huge perched aquifers (with volume tens of to hundreds m^3) are known both from the Moravian both the Bohemian karst.

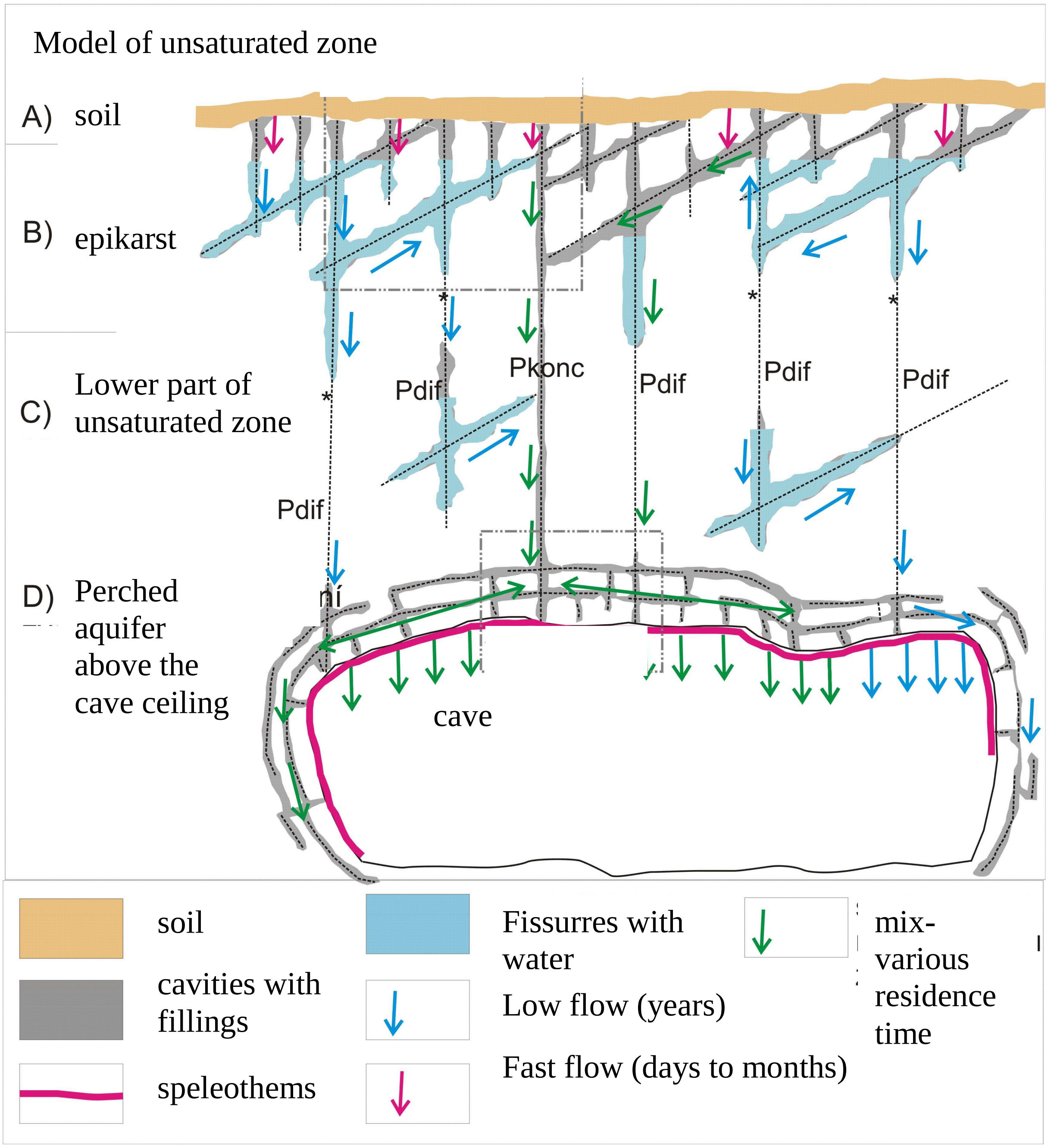

Figure 9. Storativity and depth below the ground Conceptual model of flow in unsaturated zone above the Ochoz cave. Model is a scheme, thickness of individual reservoirs are not realistic.
Arrows of both directions show zone of water mixing. * is for fissures not widened by karstification

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Abstract

Flow and mean residence time in epikarst and unsaturated zone was studied above the Ochoz cave in the Moravian Karst.

I studied various flow components with different residence time in unsaturated zone and the influence of soil and epikarst on seepage composition and residence time by means of several methods (longterm monitoring of conductivity, flowrate of seepage and soil water, use of environmental tracers - ^{18}O, ^{3}H, CFC and SF_6, flow into the soil and detailed sampling during intesive rain events). Seepage sites Kašna in the Rudické propadání cave system and Mapa Republiky in Býčí skála were reference localities in unsaturated zone. For comparison I modeled residence time in saturated zone: at Kaprálka outlet close to the Ochoz cave, at Stará řeka (Rudické propadání) and Konstantní přítok (Amatérská cave). Mean residence time in unsaturated zone above the Ochoz cave reaches 7 – 20 years, while it is only few months in the soil (1 – 8 months, depending on the depth). At Kašna seepage site, the reasidence time is similar to the Ochoz cave - about 18 – 20 years, at Mapa republiky seepage site, it reaches 150s year due to unusual geological settings. Mean residence time in order of 10 – 20 years corresponds to storativity values (0.6 % in average) calculated from parallel water level recession in boreholes in unsaturated zone and flowrate decrease of a local spring. Mean residence time in outlets from saturated zone, which drain water both from unsaturated and saturated zone, is 5 – 23 years. The main water storage in unsaturated zone of the Moravian karst is apparently placed above the regional water level.

Even during intensive infiltration events, pre-event water prevails in the epikarst. Monitoring of seepage conductivity and $\delta^{18}O$ composition prooved that freshly infiltrated water component doesn´t exceed 20 %.

Unsaturated zone represents a huge water reservoir. Despite significant hydraulic reaction (which spreads in tens of hours or first days after rain or snowmelting), $\delta^{18}O$ and conductivity values don´t change substantially.

Epikarst and unsaturated zone are more important reserviors for water accumulation than soil.

Based on all data a conceptual model of water flow and mixing in karst unsaturated zone was created. This model consists of four storage zones: soil reservoir, epikarst, lower unsaturated zone and perched aquifer in fissures above the cave ceiling.