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Autoreferát disertační práce
Summary of the Doctoral thesis

Vlhkostní charakteristiky přirozených pískovcových výchozů
Moisture characteristics of natural sandstone exposures

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Abstrakt

Vlhkost v pískovci hraje důležitou roli v hydrologických, zvětrávacích, biologických a dalších procesech. Znalosti o výskytu a pohybu vlhkosti v porézním prostředí přirozených pískovcových výchozů jsou však značně strohé. Cílem doktorské práce proto bylo kvantifikovat vybrané vlhkostní charakteristiky několika přirozených pískovcových výchozů v Českém ráji (Česká republika).

Podle režimního měření se průměrná roční teplota v pískovcových skalních městech pohybovala od 8,5 °C do 11,5 °C a relativní vlhkost vzduchu od 73 % do 85 %, přičemž odlesněná oblast vykazovala teplejší a sušší mikroklima a větší amplitudu hodnot než zalesněné oblasti. Byly zjištěny hodnoty objemové vlhkosti (více než 400 měření) a sacího tlaku (více než 150 měření) pískovcových výchozů a jejich změny v čase a prostoru. Průměrná objemová vlhkost se v zóně od povrchu pískovce do hloubky 12 cm pohybovala od 3 % do 10 % a sací tlak se v hloubce 2–12 cm pohyboval od 2 kPa až nad 130 kPa.

Pro určení prostorového uspořádání vlhkosti u pískovcového povrchu bylo poprvé opakovaně využito metody obarvování práškem uraninu. Podle obarvení se pískovcové prostředí rozdělilo na kapilární (vlhkou) a difuzní (suchou) zónu, na jejichž ostrém rozhraní se nacházela výparová fronta. Pozice výparové fronty se pohybovala od povrchu pískovce až do hloubky 9,5 cm, přičemž platilo, že čím blíže k povrchu v dlouhodobém průměru byla, tím méně kolísala její pozice v čase.

Pomocí přímého měření výparovými aparáty a taktéž díky výpočtům podle Fickova zákona byla poprvé určena intenzita výparu z pískovcového prostředí a její proměnlivost v čase a prostoru. Relativní chyba výpočtů byla 9 % až 58 % z měřené hodnoty, což je při vysoké variabilitě intenzity výparu (tři řády) přijatelná nejistota. Průměrná roční intenzita výparu se v jednotlivých oblastech pohybovala od 3 $mm.rok^{-1}$ do 245 $mm.rok^{-1}$. O intenzitě výparu nejvíce rozhodovala aktuální

hloubka výparové fronty, dále roční období a teprve poté mikroklima dané oblasti.
Bylo zjištěno, že biogenní skalní kůra ovlivňuje některé hydraulické vlastnosti pískovce. Saturovaná hydraulická vodivost byla biogenní skalní kůrou statisticky významně snížena (15×–300×), stejně jako rychlost kapilárního nasákávání (2×–33× podle laboratorního měření, 5×–11× podle terénního měření). Díky svým hydrofobním vlastnostem tak biogenní skalní kůra může působit jako významný brzdící mechanismus toku kapilární vody u pískovcového povrchu, a tím ovlivňovat mnoho procesů. Oproti tomu propustnost materiálu pro vodní páru nebyla biogenní skalní kůrou statisticky významně ovlivněna.

Abstract

Moisture in a sandstone body plays a notable role in hydrological, weathering, biological and other processes. Knowledge about presence and movement of moisture within porous medium of natural sandstone exposures is, however, rather limited. Aim of the doctoral thesis was thus to quantify selected moisture characteristics of several natural sandstone exposures in Český ráj (Czech Republic).

According to long-term logging, mean annual temperature at studied areas was between 8.5 °C to 11.5 °C, mean annual relative humidity was between 73 % to 85 %. Deforested area was found warmer and drier and amplitude of the values was higher there than at the forested areas. Values of water content (more than 400 measurements) and suction (more than 150 measurements) of the exposures including their spatial-temporal changes were obtained. Mean volumetric water content in zone from the sandstone's surface to 12 cm depth was from 3 % to 10 % and mean suction in depth 2–12 cm was from 2 kPa to more than 130 kPa.

Using uranine powder coloring, spatial distribution of moisture near the sandstone's surface was visualized repeatedly for the first time. The coloring divided the surficial area of the sandstone into capillary (wet) and diffusion (dry) zone. The sharp transition between the two zones was represented by vaporization plane. The vaporization plane position varied from very surface to the depth of 9.5 cm, whereas the closer to the sandstone's surface in long-term average, the lesser the vaporization plane depth varied in time.

Based on direct measuring using evaporation apparatuses and on calculations by Fick's law, the evaporation rate from sandstone and its variability were obtained for the first time. The relative error of the calculations was from 9 % to 58 % of the measured value, which is acceptable error as observed evaporation rate varies over 3 orders of magnitude. Mean annual evaporation rate varied from 3 mm×year^{-1} to 245 mm×year^{-1}. The most important factor controlling the evaporation rate

was the vaporization plane depth below the surface. Then the season followed and the factor which controlled the evaporation rate least was the microclimate given by the location.

It was revealed that biologically-initiated rock crust affects some hydraulic properties of the sandstone. Saturated hydraulic conductivity was statistically significantly decreased (15×–300×) as well as the capillary water absorption (2×–33× according to laboratory measurements, 5×–11× according to field measurements). Thanks to its hydrophobic properties, biologically-initiated rock crust can act as a factor notably decelerating the capillary water flow near the sandstone's surface and thus affects many processes. On the other hand, water-vapor diffusion was not significantly influenced by the biologically-initiated rock crust.

Table of content

1. Introduction

Presence of moisture and its movement in a sandstone body play a notable role in hydrological (Domenico and Schwartz, 1998), biological (Viitanen et al., 2010; Bellinzoni et al., 2013), weathering (Goudie and Viles, 1997; Paradise, 2002; Mol and Viles, 2012) and other processes. It is well-known that moisture and its spatial distribution in a sandstone control the degree of rock disintegration during frost and salt weathering. With increasing water content, the degree of damage owing to frost weathering increases (Hallet, 1983; Hall, 1988). The places of pore water evaporation are equal to places of potential salt weathering (Huinink, 2004; Schnepfleitner, 2016).

Despite the important role of moisture in many processes, there is a lack of information concerning its presence and movement in sandstone bodies. We lack information about the moisture supply sources and about evaporation from the sandstone body to the atmosphere. Very little is known about spatial distribution of moisture near the sandstone's surface and its variability in time. Except for several student theses (Sommerová, 2014; Svobodová, 2015; Studencová, 2017), no scientific publication dealt with measuring suction, water content and moisture distribution within the sandstone exposures for long period of time. Therefore, many factors affecting the presence and movement of moisture in the natural sandstone exposures might be overlooked.

2. Aims of the study

Aim of the presented thesis is to quantify selected moisture characteristics of several natural sandstone exposures in Český ráj ("Bohemian Paradise", Czech Republic). The studied moisture characteristics were water content, suction and their spatial-temporal changes, spatial distribution of capillary and dry zones near the sandstone's surface and evaporation rate from sandstone bodies. The moisture characteristics may serve as an input data for conceptual model of interaction between weathering and moisture.

Partial aims of the thesis were: i) to utilize data from temperature and relative humidity monitoring and depth of vaporization plane for prediction of evaporation rate; ii) to utilize recent method for visualization places of evaporation, and iii) to quantify the effect of biologically-initiated rock crust on hydraulic properties of the studied sandstone.

3. Material and methods

The research was focused on quartz sandstone from Bohemian Cretaceous Basin, both *in situ* and in laboratory using sampled cores of the sandstone. In total, four main study sites with natural sandstone exposures and one study site in Střeleč sandstone quarry in Český ráj were selected for the research.

The air temperature and relative humidity were monitored at the studied sites at the outer surfaces of the sandstone's exposures using data-loggers (four locations for three and half a years). Two different site types were included: shaded sites covered with a forest canopy (forested areas), and a site exposed to direct solar radiation (deforested area with rock outcrops exposed to solar radiation).

The sandstone cores were sampled using a hand drilling machine equipped with a diamond crown core drill, in a rotational mode, without percussion and without the use of water as a coolant. The sampled cores were 67 mm or 83 mm in diameter, their length was 20 mm to 70 mm. In some cases, two cores were sampled in a row, one representing the surficial zone ("outer core"), one representing the underlying material ("inner core").

The cores were weighted after the sampling, dried at laboratory conditions (relative humidity ~40 %). Ambient moisture was calculated from the decrease of their weight (gravimetric method). Time Domain

Reflectometry (TDR) was used in the field to measure ambient water content of the exposures. TDR method uses two 12 cm long metal needles, which are put into holes drilled in a sandstone exposure, it measures an average water content along this length. To estimate water content in very shallow zone of the sandstone, protimeter was used. Using miniature tensiometer, the suction in the depths from 2 cm to 12 cm below the sandstone's surface was determined.

Using uranine powder coloring (Bruthans et al., 2018; Weiss et al., 2018), spatial distribution of moisture near the sandstone's surface was visualized. Into sides of the holes (20 mm to 80 mm in diameter) freshly drilled into the sandstone surface, red uranine powder was immediately applied (Fig. 1). The coloring divided the surficial area of the sandstone into i) capillary (wet) zone, where the powder dissolved and changed its color from red to dark orange, and ii) diffusion (dry) zone, where the powder did not dissolve and thus remained red. The sharp transition between the two zones was represented by vaporization plane where evaporation of pore water occurs (Or et al., 2013). The holes were photo-documented after the coloring and the depth of the vaporization plane was recorded.

In the laboratory, using modified method of wet cup (EN ISO 12572:2001), water-vapor permeability of the sandstone was measured. Based on partial vapor pressure gradient imposed in the sandstone core, the water-vapor diffused through the core, and the amount of diffused water-vapor per unit time was quantified.

Saturated hydraulic conductivity was measured at cores under constant hydraulic gradient. To prevent the effect of air-bubbles on hydraulic conductivity, the cores were vacuum-saturated, and the water used for the measurements was boiled and cooled just before measurements were taken.

To measure capillary water absorption in laboratory, the sandstone cores were hanged on a hanging weight with their bottom base in a contact with water surface. The hanging weight continuously recorded increasing weight of the sample caused by absorbing the water. In the field, the capillary water absorption was measured using Karsten tube (Hendrickx, 2013).

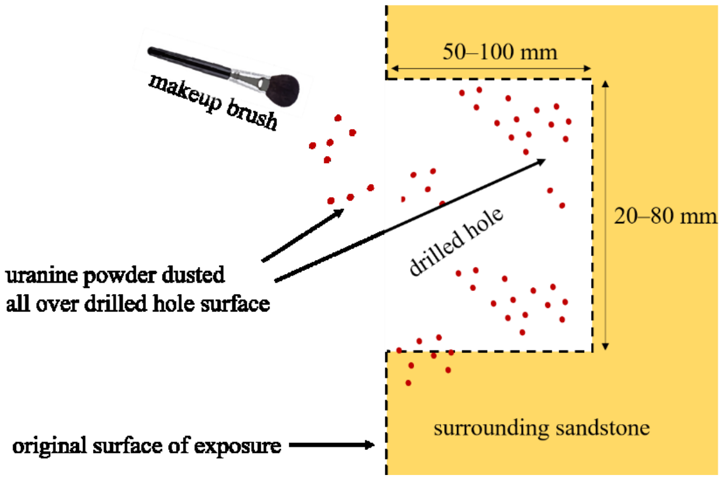

Fig. 1. Scheme of visualizing spatial distribution of moisture near the sandstone surface (modified from Weiss et al., 2018).

Water-vapor permeability, saturated hydraulic conductivity and capillary water absorption were measured to quantify the effect of the biologically-initiated rock crust on these properties. To fulfill this, both outer cores (with the crust) and inner cores (without the crust) were measured in pairs, compared to each other and the values were subsequently calculated for the crust itself and statistically tested using Student t-test with significance level of 0.05. For details of the methods, see Slavík et al. (2017).

The evaporation rate from the sandstone was measured *in situ* using two types of evaporation apparatuses. In the first one, the vaporization plane was set few centimeters below the surface (dry core), and in the second one, the vaporization plane was at the very surface of the sandstone (wet core; Fig. 2).

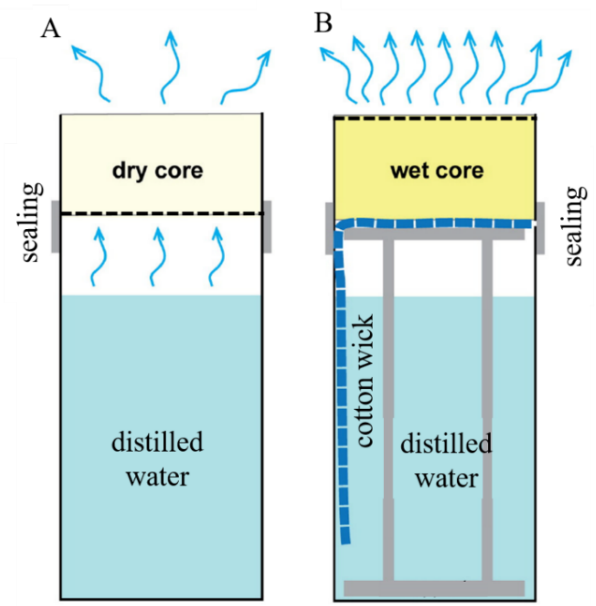

Fig. 2. Evaporation apparatuses for measuring evaporation rate: a) dry core with the vaporization plane at the bottom base of the core, b) wet core with the vaporization plane at the upper base of the core. The vaporization plane position is visualized by the dashed line. Modified from Bruthans et al. (2018).

Evaporation rate from loose porous medium is commonly calculated by Fick's law for water-vapor diffusion (for details see e.g. review by Or et al., 2013). Using this approach, evaporation rate from sandstone body (E) was calculated (Eq. 1). For the calculation, following parameters directly measured in the field (or taken from foreign studies in exceptional cases) were used: water vapor diffusion coefficient δ (s) standing for water-vapor permeability of the sandstone, temperature T (°C), relative humidity (%) and depth of the vaporization plane d (cm). Based on calibration, for the case of the vaporization plane situated at the very surface, non-zero value d = 0,08 cm was set.

$$E = \frac{\delta \Delta P}{d} \qquad (1)$$

In the (Eq. 1), ΔP (kPa) stands for the difference of partial vapor pressure between sandstone's surface and the depth equal to the depth of the vaporization plane. For saturated water-vapor, P is given by Tetens equation (1930; Eq. 2). Using density of water ($kg.dm^{-3}$) and definition of rainfall ($1\ mm = 1\ l \times m^{-2}$), one can express the calculated value E in units of $mm \times s^{-1}$ (which is equal to $kg \times m^{-2} \times s^{-1}$). (Eq. 1) is applicable for $d > 0$.

$$P = 0{,}61078 \exp \frac{17{,}27\ T}{T + 237{,}3} \qquad (2)$$

For unsaturated water-vapor, partial vapor pressure can be recalculated according to relative humidity; e.g. if the relative humidity is 70 %, actual partial vapor pressure is 70 % of the saturated partial vapor pressure value.

4. Results and discussion

4.1. Microclimate of sandstone areas

At the studied sites, air temperature and relative humidity were recorded for three and a half years every 30 minutes using dataloggers. The specific microclimate of forested areas was not affected by differences in altitude (240–430 m a.s.l.), in forest tree composition nor aspect of the sandstone exposures.

Mean annual temperature at forested areas was from 8.5 °C to 8.7 °C, mean annual relative humidity was from 83 % to 85 %. At deforested area, mean annual temperature was 3 °C higher and mean annual relative humidity 10 % lower. The temperature and relative humidity varied more at the deforested area than at the forested ones both daily and yearly. At the forested area, very low speed of wind was often observed (less than ~0.4 $m \times s^{-1}$), with very rare maximums of 2 $m \times s^{-1}$.

At the deforested warmer area, 26 freezing-thawing cycles were detected in 2017, while at forested colder area it was only 17 of them. The freezing-thawing cycle is defined here as six and more hours of freezing followed by at least four hours with temperature above the freezing point. The difference in number of freezing-thawing cycles was caused by rather stable temperature below the freezing point at the forested area in January, while at the deforested area the temperature commonly increased above the freezing point due to direct solar radiation in the daytime.

4.2. Water content and suction

Long-term measuring with TDR, protimeter and miniature tensiometers provided values of water content, suction and their spatial-temporal changes in natural sandstone exposures. From more than 200 individual measurements at 19 individual locations, mean volumetric water content in zone from the sandstone surface to 12 cm depth was from 3 to 10 vol. %. From more than 150 individual measurements at 13 locations, mean suction in depth from 2 cm to 12 cm was from 2 kPa to more than 130 kPa. Exposures in caves and cracks and/or with apparent salt efflorescence were found to be the wettest ones. On the other hand, the solitaire pillar protruding from surrounding massif, exposures exposed to direct solar radiation and not protected from strong wind were the driest ones.

Values of water content in the Střeleč quarry provided by TDR (more than 50 measurements) were compared to values obtained from gravimetric method (more than 200 measurements), which is generally accepted as a precise method. The comparison revealed that values obtained from both methods are in a good agreement. It was also revealed by long-term gravimetric water content monitoring that biologically-initiated rock crust only occurs on surfaces where the water content did not drop below ~1 vol. %.

The TDR water content values considered as an average in the zone from surface to depth of 12 cm varied less than the values at the sandstone surface measured by the protimeter, both in time and space. This is probably caused by higher variability of sandstone water content near the surface.

4.3. Spatial distribution of moisture in sandstone exposures

Using uranine powder coloring method, spatial distribution of moisture near the sandstone surface was visualized at 10 different locations using more than 30 individual measurements. The coloring divided the surficial area of the sandstone into capillary (wet) zone and diffusion (dry) zone. The sharp transition between the two zones was represented by vaporization plane (Fig. 3).

The vaporization plane position varied from very surface of the sandstone to the depth of 9.5 cm. The closer the vaporization plane to the surface in long-term average, the lesser its depth varied in time. Actual position of the vaporization plane is probably given by the ratio between moisture supply and evaporation rate from the sandstone.

At the two wettest exposures, the vaporization plane was always found at the very sandstone surface. In the case of exposure with salt efflorescence, the vaporization plane depth was always just below the surface. The deepest vaporization plane was found in the driest, solitaire pillar protruding from surrounding massif. The obtained values are first values of vaporization plane's depths in the sandstone areas in Český ráj. Measured values were also used for calculating the evaporation rate from sandstone exposures.

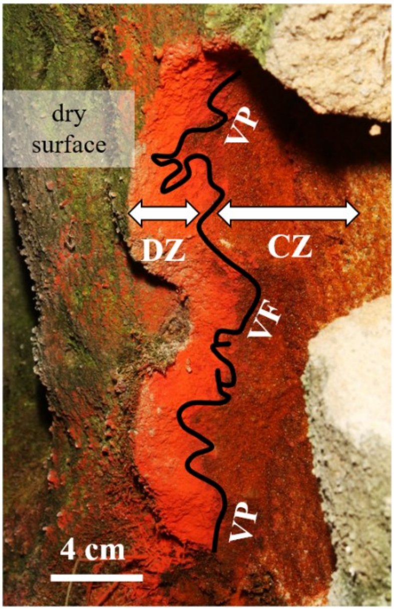

Fig. 3. Visualization of the vaporization plane depth by uranine powder coloring method. DZ – diffusion zone (dark orange), CZ – capillary zone (red), VP – vaporization plane (the transition between DZ and CZ). Modified from Weiss et al. (2018).

4.4. Evaporation from sandstone body

Using two types of evaporation apparatuses with the vaporization plane i) at the very surface, ii) few centimeters below the surface (Fig. 2), the evaporation rate from sandstone body was measured *in situ* for the first time. Values of evaporation rate and its seasonal variation were obtained from 20 individual measurements in the forested area. In the deforested area, the measurement was not successful due to inrush of rain water into the apparatuses.

The measured evaporation rate in the case i) varied from ~63 mm×year^{-1} to ~720 mm×year^{-1} during the year. In the case ii) the evaporation rate varied from ~2 mm×year^{-1} to ~10 mm×year^{-1} during the year. The position of the vaporization plane thus notably affected the evaporation rate. Higher evaporation rate was observed in warm period of year.

The evaporation rate was also calculated using Fick's law based on (Eq. 1). In the first step, it was revealed by comparison of the calculated values with the measured ones, that relative error of the calculation is from 9 % to 58 % (e.g. Fig. 4) which is acceptable error as evaporation rate varies over 3 orders of magnitude and recently there are not even rough estimates available. The relative error was obtained from more than 150 values in total.

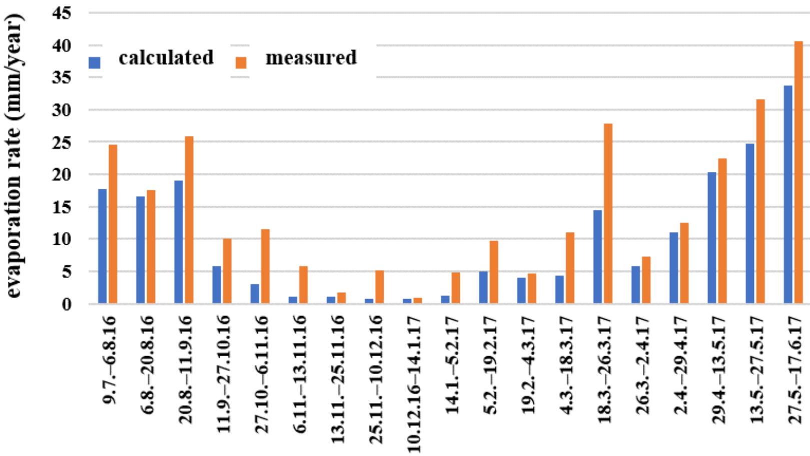

Fig. 4. Example of comparison between calculated and measured values of evaporation rate.

In the second step, the evaporation rate was calculated for four main study sites using water vapor diffusion coefficient, logged data of temperature and relative humidity and occasional measurements of vaporization plane. Mean annual calculated evaporation rate in year 2017 was from 3 mm×year^{-1} to 245 mm×year^{-1}, with values varying vastly both in time and space. It is the first estimate of the evaporation rate from the sandstone bodies to my knowledge. In the range of the observed values, the most important factor controlling the evaporation rate was the vaporization plane depth below the surface. Then the season followed and the factor which controlled the evaporation rate least was the microclimate given by the location. The vaporization plane depth is capable to control the evaporation rate over many orders of magnitude, so it is critical to measure its depth regularly for obtaining accurate calculations.

4.5. Effect of biologically-initiated rock crust on hydraulic properties

It is well-known that presence of biologically-enriched surface crust can strongly alter hydraulic properties of the porous medium (e.g. Seifert and Engesgaard, 2012). Nevertheless, not much is known about the effect of biological coatings on sandstones. From this reason it was studied how the hydraulic properties of the studied sandstone are affected by the presence of biologically-initiated rock crust.

For the first time, the effect of biologically-initiated rock crust on hydraulic properties of sandstone was quantified by recalculation from a pair of cores (inner core without the crust and outer core with the crust). Its effect was statistically tested using Student t-test with significance level of 0.05. Saturated hydraulic conductivity was significantly decreased (15×–300×) by the biologically-initiated rock crust, as well as the capillary water absorption (2×–33× according to laboratory measurements, 5×–11× according to Karsten tube field measurements). Thanks to its hydrophobic properties (Slavík et al., 2017), biologically-initiated rock crust can act as a factor significantly decelerating the capillary water flow near the sandstone surface, and thus affects most of the processes controlled by water content and flux. On the other hand, water-vapor diffusion was not significantly influenced by the biologically-initiated rock crust.

5. Conclusions

Moisture in a sandstone body plays an important role in hydrological, weathering, biological and other processes. Limited information was available on presence and movement of moisture within porous medium of natural sandstone exposures. Therefore, selected moisture characteristics of several natural sandstone exposures were determined. The research was carried out mainly at four locations in Český ráj ("Bohemian Paradise", Czech Republic) and in the active sandstone quarry Střeleč.

Based on almost three and a half years logging of relative humidity and temperature measured each 30 minutes, microclimatic conditions of the studied sandstone areas were determined. Using several methods originally used in pedology (such as TDR, miniature tensiometers), long-term measurements of water content and suction were taken. Mean volumetric water content in zone from the sandstone's surface to 12 cm depth was from 3 % to 10 % (more than 200 measurements) and mean suction in depth 2–12 cm was from 2 kPa to more than 130 kPa (more than 150 measurements).

Repeated visualization of moisture distribution within the sandstone exposures was provided for the first time using uranine powder coloring. It was shown that the near subsurface of the sandstone is divided into capillary (wet) zone and diffusion (dry) zone, with sharp transition between the two zones represented by vaporization plane. The vaporization plane position below the sandstone's surface varied both in time and space.

Based on direct measurements using evaporation apparatuses and based on calculation by Fick's law, the evaporation rate from the sandstone and its variability were obtained. From more than 140 values in total, the relative error of the calculations was from 9 % to 58 % which is acceptable error as evaporation rate varies over 3 orders of magnitude and

until recently, there were not even rough estimates available. Calculated mean annual evaporation rate was oscillating between 3 mm×year^{-1} and 245 mm×year^{-1}, varying vastly both in time and space. In the range of the observed values, the most important factor controlling the evaporation rate was the vaporization plane depth below the surface. Then the season followed and the factor which controlled the evaporation rate least was the microclimate given by the location.
It was revealed from measuring of hydraulic properties (statistical processing using more than 70 individual values), that the biologically-initiated rock crust significantly reduces saturated hydraulic conductivity and capillary water absorption, which markedly affects most of the processes controlled by moisture content and flux near the sandstone's surface. On the other hand, the biologically-initiated rock crust had no measurable influence on the diffusion of water-vapor.

Acknowledgments
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7. Curriculum vitae

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2015–present: Measurement of tritium activity in Isotope laboratory, Faculty of Science, Charles University.
2013–present: Work on grant projects GA CR No. 13-28040S, 16-19459S and 19-14082S, and GA UK No. 1046217, more than 70 days of field research abroad.

Research area
Unsaturated zone, Isotope methods in hydrogeology, Evaporation

8. Publications

Slavík, M., Bruthans, J., Filippi, M., Schweigstillová, J., Falteisek, L., Řihošek, J. (2017). Biologically-initiated rock crust on sandstone: Mechanical and hydraulic properties and resistance to erosion. Geomorphology 278, 298–313. (Q1, IF = 2.958)

Slavík, M., Bruthans, J., Schweigstillová, J., Falteisek, L. (2017). Impact of biocolonization on erosion and resistance of different types of sandstone surfaces in a quarry and in natural outcrops. Geoscience Research Reports 50, 81–87 (in Czech).

Slavík, M., Bruthans, J., Kobrlová, A., Vorlíček, P., Paděra, M. (2017). Hydraulic properties of biologically initiated rock crust on sandstone. Geoscience Research Reports 50, 117–123 (in Czech).

Bruthans, J., Filippi, M., Slavík, M., Svobodová, E. (2018). Origin of honeycombs: testing hydraulic and case hardening hypotheses. Geomorphology 303, 68–83. (Q1, IF = 2.958)

Filippi, M., Bruthans, J., Řihošek, J., Slavík, M., Adamovič, J., Mašín, D. (2018). Arcades: products of stress-controlled and discontinuity-related weathering. Earth-Science Reviews 180, 159–184. (Q1, IF = 7.051)

Weiss, T., Slavík, M., Bruthans, J. (2018). Use of sodium fluorescein dye to visualize the vaporization plane within porous media. Journal of Hydrology 565, 331–340. (Q1, IF = 3.727)

Řihošek, J., Slavík, M., Bruthans, J., Filippi, M. (2018). Evolution of natural rock arches: A realistic small-scale experiment. Geology 4(1), 71–74. (Q1, IF = 5.073)

Kůrková, I., Bruthans, J., Balák, F., Slavík, M., Schweigstillová, J., Bruthansová, J., Mikuš, P., Vojtíšek, J., Grundloch, J. (accepted). Factors controlling evolution of karst conduits in sandy limestone and calcareous sandstone (Turnov area, Czech Republic). Journal of Hydrology. (Q1, IF = 3.727)