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RESEARCH PAPER

Moisture and temperature in a proppant-enveloped silt block of a recharge dam reservoir: Laboratory experiment and 1-D mathematical modelling

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مستوى الرطوبة والحرارة في الكتل الطمية المغلفة بالرمل في بحيرة سد التغذية: تجربة معملية ونمذجة تحليلية أحادية البعد

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ABSTRACT. Mosaic 3-D cascade of parallelepiped-shaped silt blocks, which sandwich sand-filled cracks, has been discovered in the field and tested in lab experiments. Controlled wetting-drying of these blocks, collected from a dam reservoir, mimics field ponding-desiccation conditions of the topsoil layer subject to caustic solar radiation, high temperature and wind, typical in the Batinah region of Oman. In 1-D analytical modelling of a transient Richards' equation for vertical evaporation, the method of small perturbations is applied, assuming that the relative permeability is Averyanov's 3.5-power function of the moisture content and capillary pressure is a given (measured) function. A linearized advective dispersion equation is solved with respect to the second term in the series expansion of the moisture content as a function of spatial coordinates and time. For a single block of a finite thickness we solve a boundary value problem with a no-flow condition at the bottom and a constant moisture content at the surface. Preliminary comparisons with theta-, TDR- probes measuring the moisture content and temperature at several in-block points are made. Results corroborate that a 3-D heterogeneity of soil physical properties, in particular, horizontal and vertical capillary barriers emerging on the interfaces between silt and sand generate eco-niches with stored soil water compartments favourable for lush vegetation in desert conditions. Desiccation significantly increases the temperature in the blocks and re-wetting of the blocks reduces the daily average and peak temperatures, the latter by almost 15°C. This is important for planning irrigation in smartly designed soil substrates and sustainability of wild plants in the region where the top soil peak temperature in the study area exceeds 70°C in Summer but smartly structured soils maintain lash vegetation. The layer of dry top-blocks acts as a thermal insulator for the subjacent layers of wet blocks that may host the root zone of woody species.

KEYWORDS: Soil capillary barrier; soil heterogeneity; hydropedology; soil moisture content; linearized Richards' equation.

الملخص: خلال دراسة التغييرات في تربة سد الخوض تم العثور على تشكيله فريدة للتربة الطمية ذات النمط الكتلي ذو الأسطح المتعددة والمغلفة بالرمل، والتي تشكلت بفعل عوامل عديدة منها طوبوغرافية السطح وترسبات الطمي والرمل لمياه الفيضانات ذات السلوك غير المنتظم. تم دراسة سلوك الماء والحرارة في هذه الكتل مخبريا وباستخدام النمذجة التحليلية. صممت التجربة لكي تحاكي الوضع في سد التغذية وذلك بالتحكم في دورات الرطوبة والجفاف للكتل الطمية وتعريضها للإشعاع الشمسي ودرجات الحرارة المرتفعة. كما تم استخدام معادلة ريتشارد الخطية لحساب معدل البخر العمودي باعتبار ثابت أفيرنيانوف لرطوبة التربة هو ٣,٥ وأما ثابت الضغط الشعري فتم قياسه أيضا. تم مقارنة نتائج التجارب المعملية مع نتائج النمذجة التحليلي وأثبتت النتائج تأثير الحواجز الشعرية للتربة خاصة للأسطح البينية للطمي والرمل، والتي أدت إلى الاحتفاظ بماء التربة كحويصلات توفر المياه للأعشاب والشجيرات في البيئة الصحراوية، وأدى جفاف التربة إلى رفع درجة حرارة الكتل الطمية كما أن إعادة ترطيب التربة ساعد على خفض معدلات درجة الحرارة اليومية وخفض الدرجة القصوى بمعدل ١٥ درجة مئوية. لقد أوجدت طبقات الرمل المحيطة بالكتل الطمية حاجزا حراريا وهيدرولوجيا يعيق خروج الماء من الكتل إلى طبقات الرمل وبالتالي أعاق عملية التبخر، مما أدى إلى بقاء الماء في الكتل الطمية والذي يعد مهما للري وديمومة الزراعة في بيئة تصل درجة حرارة تربتها إلى ٧٠ درجة مئوية في فترة الصيف.

الكلمات المفتاحية: معادلة ريتشارد الخطية، محتوى رطوبة التربة، هيدروبيدولوجي، التربة الغير متجانسة، الحواجز الشعرية للتربة

Introduction

Layering, i.e. vertical alternation of textures with distinct interfaces between layers, is the backbone of soil sciences in applications to agronomy and ecohydrology (see e.g. Connolly, 1998, Noy-Meir, 1973). In soil physics, water upward-downward fluxes (evaporation-infiltration-redistribution) are usually considered as 1-D steady or transient phenomena, with effective water conductance-capillarity properties derived by conjugation of individual layers of the soil profile (see e.g., Assouline et al., 2014, Fehmi and Kong, 2012, Gardner and Fireman 1958, Hillel and Talpaz, 1977, Khan, 1988, Ripple et al., 1970, Willis, 1960, Warrick and Yeh, 1990, Wuest and Schillinger, 2011, Zhu and Warrick, 2012).

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Spatially patchy, i.e. 2-D and time-wise persistent distributions of the volumetric moisture content (VMC) in a seemingly homogeneous topsoil have been discovered and described on the scale of a mini-watershed/cultivated field and attributed to soil aggregates (Guber et al., 2003, Pachepsky et al. 2005), i.e. a 3-D composite with a size of an elementary cell (aggregate) of several millimeters, which is superior in terms of soil water dynamics as compared to unstructured soils (see e.g. Sawiñski et al., 2011). Lehman and Or (2009, 2013) studied a similar phenomenon of 2-D patchy textural pattern of the soil (macroscale) and pore bundles (microscale), which conduct and evaporate moisture in a spatially mosaic way. Al-Ismaily et al., (2013), discovered an essentially 3-D and temporarily very stable patchiness of the soil-structure, which is not detectable by standard on-surface measurements of the moisture content or evaporation rate i.e. by such common instruments as theta-probes, surface-mounted tensiometers or evaporimeters. Hereafter this structure is called a "smart design". This patchiness becomes evident either in pedons of 1.5-2.0 m deep or by observing distinct ecotones of emerging vegetation. The vegetation, as a proxy-indicator of structural heterogeneity, serves as a footprint, with high transpiration detectable by sapflow meters. The cascades of silty blocks of sizes of 30-40 cm and cracks of apertures of up to several cm (Fig. 1A) were found in pedons dug inside the reservoir of the Al-Khod recharge dam in Oman. The cracks were filled with a medium-size sand, which, by analogy with fracking in reservoir engineering, is called a "proppant". Consequently, the whole cascade of the soil structure is a triple-periodic composite, with sharp contrasts of hydraulic and thermal properties between texturally contrasting components (blocks and filled fractures). Al-Ismaily et al., (2015), Al-Maktoumi et al. (2014), Al-Saqri et al. (2016) studied further hydrological and geotechnical applications of natural "smart design" patterns.

In arid regions such as Oman, both the natural and cultivated vegetation relies on the soil substrate as an eco-refuge, in the hostile ambient atmospheric conditions (Brown, 1974, Lambers et al., 2008) of annual precipitation of about 100 mm and air average temperature of about 30°C. The water deficit conjugated with heat stress and, in case of poor irrigation practices, ensued secondary soil salinization (see e.g Geng and Boufadel,

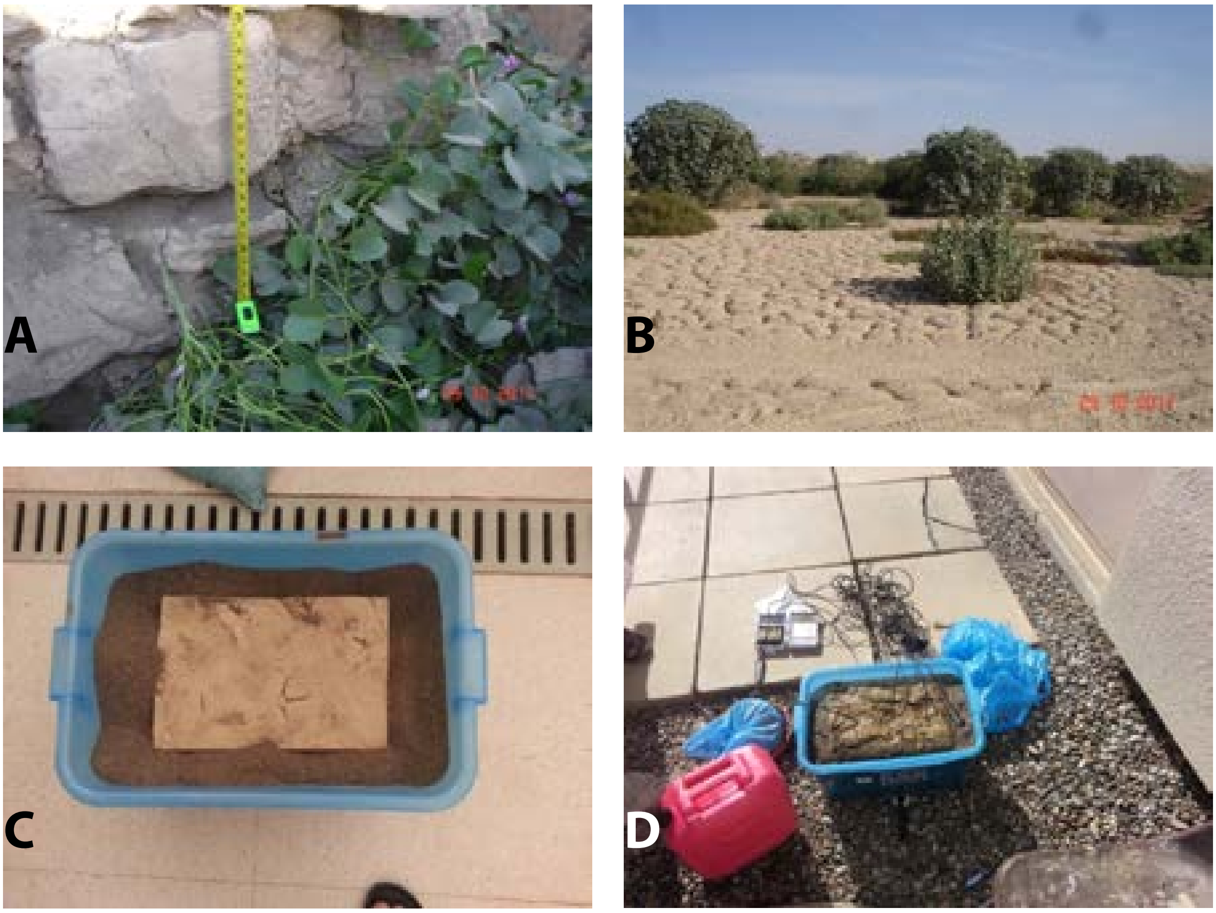

Figure 1. Smart block-fracture structure in the field and experimental replicate: (A) Silt blocks in a pedon dug in the reservoir area of the Al-Khod dam (left panel); (B) surface view of the site (right panel), (C) Silt block (light colour) collected from the reservoir and trimmed to fit the blue plastic box. Sheaths of loose sand (proppant) have darker colour, and D) Measurements of VMC-temperature after the first ponding.

2015), are eco-constraints in hot deserts, which were prognosticated to amplify in the so-called global warming scenarios (see e.g., Clair and Lynch, 2010). These constraints are mitigated by plants' adaptation in texturally heterogeneous soils, as Noy-Meir (1973) elucidated. Since his seminal paper, the temporal and spatial soil water dynamics (SWD) in hydraulically-thermally commingled soil compartments (aggregates and layers) became a topic of intensive studies in hydropedology and hydroecology (see e.g. Lin et al., 2006, Porporato and Rodriguez-Iturbe, 2002). As is evident from (Fig. 1A), right photo, woody species (e.g. castor oil plants) thrive on the "smartly designed" substrate. The top-most blocks are deadly dry and hot but starting from the second layer of blocks (see the pedon in Fig. 1A) the moisture content is amazingly high, despite a continuous transpiration by the plant roots.

Temperature distributions and heat fluxes in heterogeneous soils in temperate and relatively humid climates (Arkhangelskaya, 2012, Goncharov and Shein, 2006, Physics, 1963), where plants' cultivation is impeded by the deficit of solar radiation, are controlled by agroengineering techniques (e.g. reducing the albedo of the soil surface, its mechanical undulations, mulching, etc.) such that the topsoil serves as a heat condenser. In Oman and other arid tropics the situation is opposite: plants' roots suffer from excessive heating and, consequently, tillage, mulching, increasing albedo, subsurface irrigation and other soil-water management techniques (see e.g. Lipiec et al., 2013) serve for thermal insulation against conductive heat transfer from an extremely hot soil surface (peak temperature of which in June reaches 72-73°C in the study area) to the root zone.

The discovered "smart design" of the soil structure was replicated in an on-farm experiment and showed an excellent water saving efficiency for crop cultivation in Oman (Al-Maktoumi et al., 2014) and in growing ornamental plants as passive thermal coolers of building envelopes (Kacimov et al., 2010). The objective functions in the agroengineering design and optimization included biomass, yield and leaf-area index. Structural patchiness of the edaphic factor, band-type distribution of the plant roots and ensued transpiration and SWD was discovered and discussed in geotechnical applications by Kacimov and Brown (2015).

In this paper, we elaborate on the effect of the soil texture and structure on SWD and soil temperature. We report the results of natural evaporation and heating of one isolated silt block, collected from a reservoir site, shown in figure 1A, and sheathed by texturally the same "proppant" (wadi sand) as in Al-Ismaily et al., (2013). The main purpose was to understand how the top-most blocks of silt in (Fig. 1A) dries out and how temperature varies inside the block during this post-ponded desiccation. For this purpose, we had to quantify the capillary properties of the blocks in controlled wetting and drainage conditions. The average saturated hydraulic conductivity, k_s=0.023 m/day, of the blocks was well known from the previous experiments conducted by double-ring and tension infiltrometers and laboratory permeameter tests. In the field k_s variations within the Al-Khod dam area were reported for silt blocks in comparisons with regular soils in the off-reservoir area (Al-Saqri et al., 2016). Moreover, k_s is, generally speaking, varies vertically within any silt block because of textural variation during Stokes' sedimentation (Al-Ismaily et al., 2013). In this paper, k_s is a constant (apparent or effective) quantity and its variability is not considered in the physical and mathematical models.

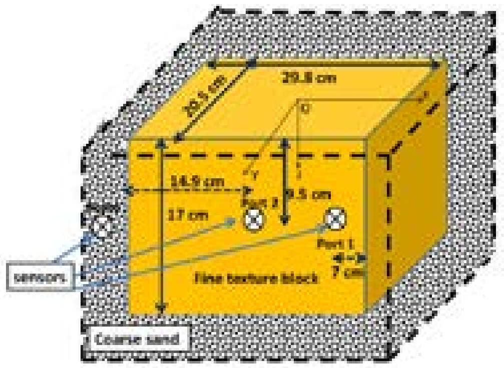

Figure 2. Sketch of the experiment in Figure 1C .

The parameters of the unsaturated conductivity and water-holding capacity of silt were parametrically involved in mathematical modelling, in which we used linearization of Richards' equation (Kulabukhova and Polubarinova-Kochina, 1959, abbreviated hereby as KPK-59). 3-D distributions of a transient moisture content within the block and "proppant", obtained from probes and modelling of 1-D flow, are important for assessing the capillary barrier phenomenon (impedance of water drainage from a wet silt to dry sand) and enhanced counter-evaporation properties of the "smart design" in (Fig. 1). Both in the field of "smartly designed" soil substrate and in our lab replication, a detailed 3-D moisture content and temperature distributions require a network of monitoring probes. In our experiment, there were only 3 functioning probes that is, of course, a serious hindrance in validation of the mathematical model.

Imbibition-desiccation experiment

A silt block was collected from the first layer of a 4-layered cascade of similar blocks (two layers separated by a thin layer of wadi sand are shown in figure 1A) from a site of the dam reservoir, which is unique from pedological, hydroecological, sedimentological and hydrological viewpoints (Al-Ismaily et al., 2013, 2015). The block was tooled into a rectangular parallelepiped to fit a plastic box. Between the box walls-bottom and the five sheathed faces of the block we put a coarse sand (see figure 1B), also collected from a wadi which crosses the

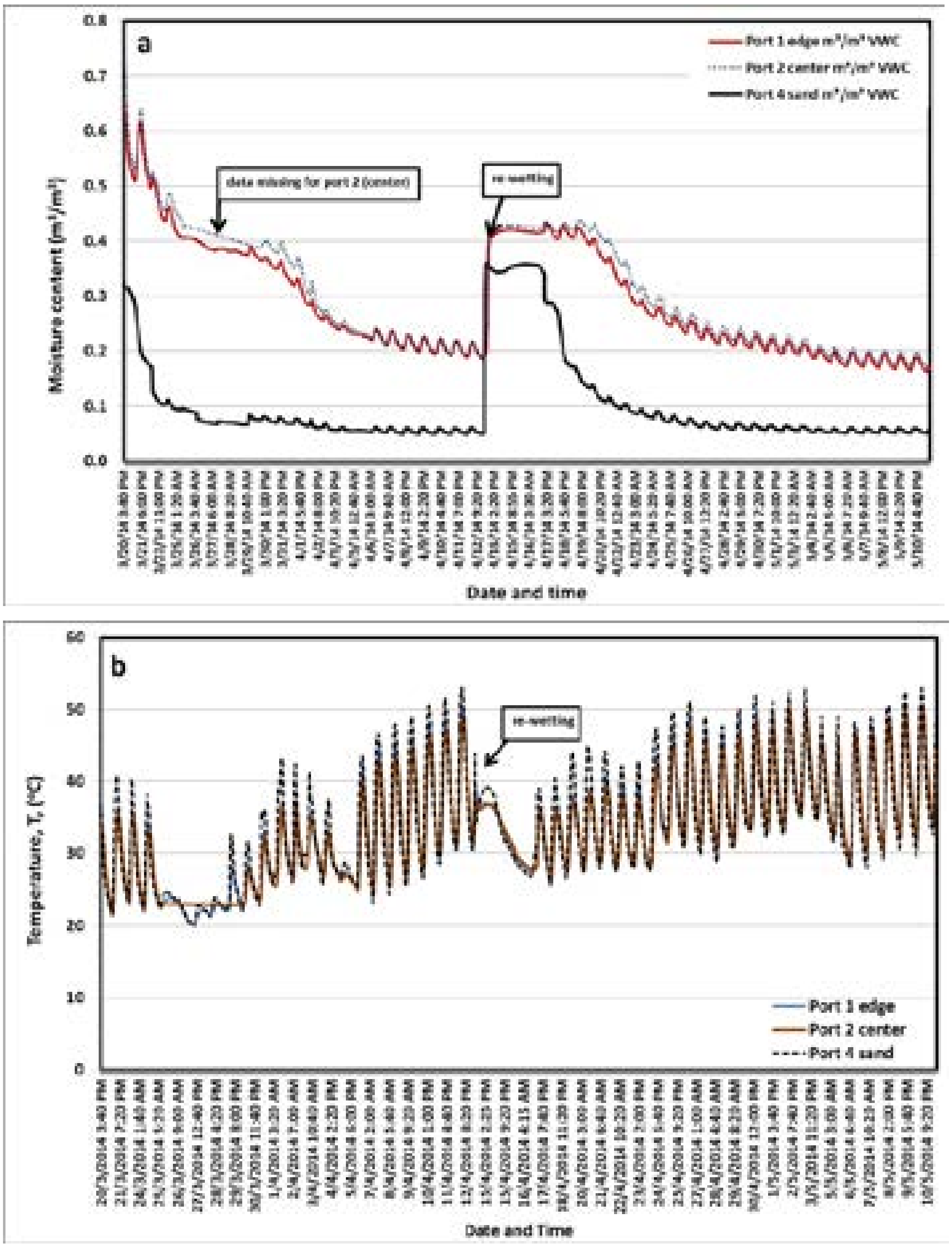

Figure 3. VMC (a) and temperature (b) as a function of time during the imbibition-dessication experiment.

dam reservoir. The upper face of the block was open to the atmosphere. Consequently, the experiment in (Fig. 1B)models the topmost blocks of (Fig. 1A)

Experimental design

A system of Cartesian coordinates Oxyz is selected as depicted in (Fig. 2). The sizes of the block and sand sheath in (Fig. 1B) as well as the loci of the probes, placed in the xOz plane of the block, are shown in (Fig. 2)

Wired sensors, connected to a data logger (5TM Sensor – Decagon Em50), were inserted into the silt and sand. A data logger, port 4 recorded information (VMC and temperature) from the sheath, port 2 – from the block centre and port 1 – from the sensor close to the silt-sand interface (Fig. 2). Probe 2 defaulted for a short time as indicated in (Fig. 3a). The experiment started with an instantaneous ponding i.e. full saturation of the dry block and the sheath. During this imbibition phase water was added and its temperature eventually equilibrated with that of the soil. After that, measurements started on March 20, 2014 at 3:40 pm. The probes recorded VMC and temperature in °C every 20 min. The first desiccation cycle lasted till April 12, 2014. On that day the system was ponded again, the block and sheath "proppant" re-saturated for two days. The second desiccation cycle started on April 16, 2014 and continued until the three VMC-curves (sand, block centre and periphery close to the silt-sand interface, see Fig. 2)

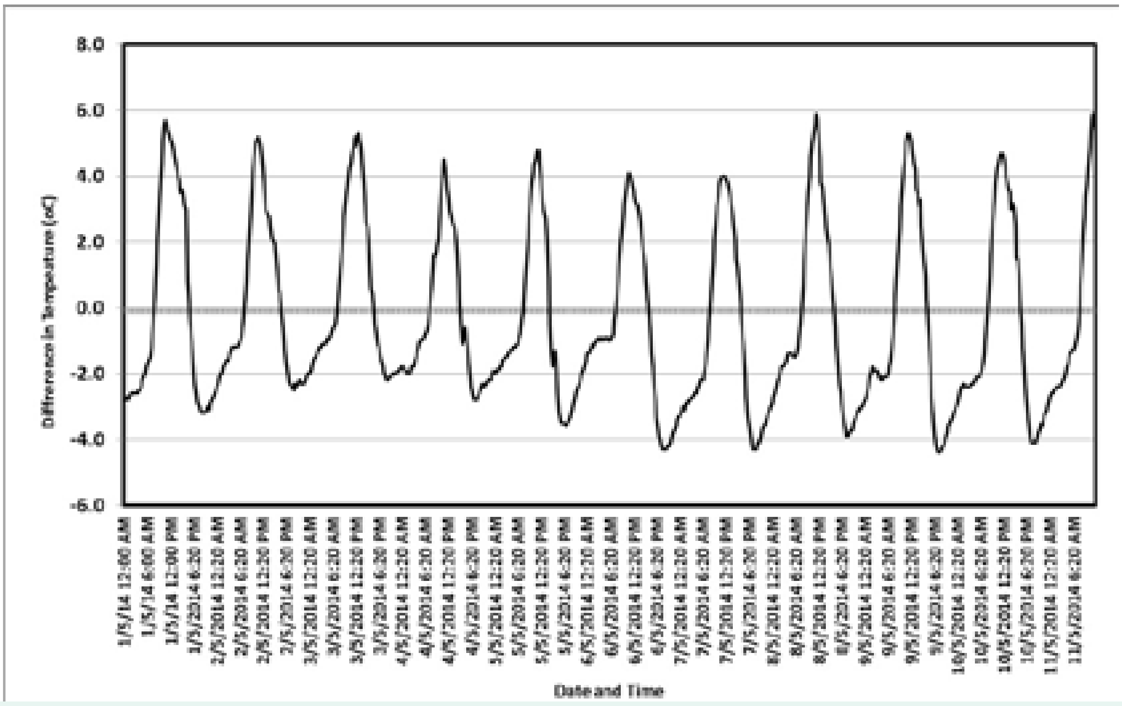

Figure 4. Difference in temperature (°C) between the sheath and the centre of the block for selected period between 1/5/2014 12:00 pm and 11/5/2014 12:00 am (after re-wetting).

reached almost horizontal asymptotes on May 10, 2014.

Figure 3a and 3b illustrates VMC and temperature curves during the two cycles of the experiment. VMC curves (Fig. 3a) have periodic blips, which reflect diurnal variations of the moisture content due to sorption-desorption of air humidity, as we witnessed in the farm experiments (Al-Maktoumi et al., 2014). As is evident from the temperature curves in (FIg. 3b), the temperature diurnally fluctuates with a general trend of an increasing daily average temperature during one post-wetting desiccation cycle. This trend is obviously caused by progressively decreasing latent heat losses due to gradually decreasing evaporation from the block surface.

The thermal gradient between the block and "proppant" becomes more pronounced as the VMC becomes low. For example, considering the period at the end of the first desiccation cycle (7th April 2014 -13th April 2014), when the VMC of 0.2 for the block and of 0.05 for the sand were recorded, the temperature difference between two points is 3-5°C while when the VMC is at saturation for both the silt and "proppant" (after rewetting on 15th April 2014), the difference in temperature is about 1°C only and less as the soil temperature equilibrates with that of the added water. The difference in VMC becomes high because the sand loses moisture faster compared to the fine textured soil of the block. Correspondingly, the difference in temperature reaches about 6°C when the difference in VMC is 0.224, considering the data of mid-day of 23rd April 2014. As the soil desiccates the temperature difference between sand and silt becomes small (around 2°C).

The thermal gradient between the block and the sand sheath reverses at night time (Fig. 4). Figure 4 plots the difference in temperature readings by the two sensors for the period from 15/4/2014 at 10:45 am to 24/4/2014 at 4:00 am. The sand is observed to cool faster during the night than the block and heated-up faster during the day. This could be attributed to variation in heat conductance as to the soil texture or to the effect of the walls through which the whole box in (Fig. 1a) loses or gains heat.

KPK-59 mathematical model of SWD

Evaporation from initially saturated soil massifs is a 3-stage, two phase (moisture and vapour), non-isothermal and transient transport of mass and energy, with complex exchanges between the top soil, atmospheric boundary layer and plant roots and periodic intervention of irrigators who induce periodic imbibition-drainage-redistribution cycles (Deol et al., 2014, Philip, 1991, Van Wijk, 1963, Shein and Goncharov, 2006). Taking into account complexity of evaporation, in this section we model isothermal SWD inside the blocks. Hysteresis of soil hydraulic properties, although evident from the two imbibition-drainage cycles in (Fig. 3a), is ignored in the KPK-59 model. As our focus is on the desiccation phase indicated in (Fig. 3), we disregard drainage of the sand and, consequently, do not conjugate flow in silt and sand. In other words we study SWD within the block only.

Geometrically, the experimental block in (Fig. 1B) mimics an elementary cell of the triple-periodic (in the domain $-\infty < x < \infty$, $-\infty < y < \infty$ and $0 < z < \infty$, see Fig. 2) cascade of blocks and "proppant"-filled cracks (Fig.1A). Physically, the natural blocks in the reservoir bed, as compared with one in (Fig. 1B), have slightly different conditions at all faces but the upper one. Namely, the side and bottom faces of the natural block are less heated than that in (Fig. 1B), which is exposed to extra heating from the four faces of the plastic box and from a hot ground surface. Another peculiarity of our experiment was in relating it to the so-called "coupled" flow of Lehman and Or (2009).

The Richards' equation for a 3-D distribution of VMC, w(x,y,z,t) [unitless], and pressure head, p(x,y,z,t) [m], inside the silt block reads:

$$\frac{\partial w}{\partial t} = \frac{\partial}{\partial x}\left(k(w)\frac{\partial p}{\partial x}\right) + \frac{\partial}{\partial y}\left(k(w)\frac{\partial p}{\partial y}\right) + \frac{\partial}{\partial z}\left(k(w)\frac{\partial p}{\partial z}\right) - \frac{\partial k(w)}{\partial z}, \qquad (1)$$

where t is time, k(w) is the unsaturated hydraulic conductivity and p(w) is the capillary pressure function (see e.g. Warrick, 2003). SWD described by eqn.(1) is isothermal. Both constituting relations, k(w) and p(w), are basic hydrophysical properties of the silt. We assumed k(w) to obey the following empiric Averyanov's relation (see KPK-59)

$$k(W) = k_s\left(\frac{w - w_0}{m - w_0}\right)^n = k_s W^n \qquad (2)$$

where W is a normalized phase saturation, w_0 is irreducible moisture content of silt, m is porosity and n is an exponent (usually assumed to be equal 3.5, see e.g. KPK-59, or pore-scale models in Al-Maktoumi et al., 2015, Kacimov and Kayumov, 2002). For p(w) the Van-Genuchten, Averyanov, Brooks-Corey or other empiric functions can be used. Pore-scale models can be also involved in derivations of both the capillary pressure function (Yang and Lu, 2012) and thermal conductivity of unsaturated soils (Youngs and Kacimov, 2007) .

KPK-59 linearized the nonlinear parabolic PDE (1) in the following manner. The phase saturation in eqn.(2) was expanded as a series:

$$W = W_0(x,y,z,t) + \lambda W_1(x,y,z,t) + \lambda^2 W_2(x,y,z,t) + \ldots, \qquad (3)$$

where λ is a parameter and W_0, W_1, W_2, are functions to be found. We assume that W_0=const, which is the initial normalized full saturation of the block in the second desiccation cycle of (Fig. 3a). The series in (3) is truncated and only the first two terms are retained. The corresponding truncations of (2) and capillary pressure curve give:

$$\begin{aligned} k(W) &= k_s W_0{}^n + \lambda n k_s W_0{}^{n-1} W_1(x,y,z,t), \\ p(W) &= p(W_0) + \lambda p'(W_0) W_1(x,y,z,t), \end{aligned} \qquad (4)$$

In the first line of eqn.(4) only the first term is retained, i.e. the unsaturated conductivity expansion is truncated as $k(W) \approx k_s W_0{}^n$. This is actually the Averyanov unsaturated conductivity function at n=3.5 (although mathematically n can be an arbitrary positive number), which is plotted elsewhere (see e.g. Polubarinova-Kochina, 1977).

The first derivative $p'(W_0)$ is a constant which, as we shall show below, is readily calculated from the selected capillary pressure function.

Taking into account eqns. (3) and (4), eqn.(1) for the first-order term in the expansion is reduced to:

$$\frac{\partial W_1}{\partial t} = D\left(\frac{\partial^2 W_1}{\partial x^2} + \frac{\partial^2 W_1}{\partial y^2} + \frac{\partial^2 W_1}{\partial z^2}\right) - u\frac{\partial W_1}{\partial z}, \qquad (5)$$

where

$$D = k_s W_0{}^n p'(W_0), \quad u = n k_s W_0{}^{n-1} \qquad (6)$$

are two constants. Obviously, eqn. (5) is a linear advective dispersion equation (ADE), in which the parameter D is "diffusivity" and u is the "convective" ("velocity") term.

Eqn.(5) should be solved in the domain

$$-a/2 < x < a/2, \quad -b/2 < y < b/2, \quad 0 < z < c \qquad (7)$$

where for our physical model in (Fig. 2)a=0.3 m, b=0.21 m and c= 0.17 m.

The boundary conditions for ADE (5) reflect a physical set-up. In arid climates, the top-soil surface z=0 dries out quickly and evaporation is controlled by soil conditions (Philip's, 1991 phase 2 of evaporation). Therefore, W=constant condition (called Dirichlet's condition) can be imposed there. In other cases, a given flux (Newman's condition) is satisfied at z=0. On the vertical and bottom faces of the block prior to the desiccation phase (see Fig. 3) for a coupled flow (i.e. within both silt and "proppant" subdomains, see Lehman and Or, 2009) the boundary condition is of the 4^{th} type that reflects the uptake of water from the sand sheath to the block (capillary siphoning). This requires conjugation of the pressure-VMC fields in both silt and sand. Our focus is on the desiccation stage in (Fig. 3a), which is most important for agronomic and hydroecological applications (Al-Ismaili et al., 2013, Al-Maktoumi et al., 2014) because the blocks, isolated by the capillary barriers, do not drain, i.e. serve as excellent storage compartments of soil water, which in the field is consumed by the plant roots. So, we consider the stages demarcated by two vertical lines in (Fig. 3 a), which indicate inception of desiccation of the blocks when the phase saturation of sand is almost constant, i.e. the Lehman-Or (2009) coupling stops but VMC in the block keeps dropping. Apparently, the only way for water to escape is to evaporate, prevalently from the z=0 face of the block (side faces of the block also evaporate but much less than the upper face).

1-D evaporation in the block

As is evident from (Fig. 3a), soon after the inception of the desiccation phase, the difference in VMC between the centre of the block and its side face becomes negligible (the blue and red curves almost coincide). This signifies the inception of a purely 1-D ascending evaporation, for which eqn.(5) is reduced to:

$$\frac{\partial W_1}{\partial t}=D\frac{\partial^2 W_1}{\partial z^2}-u\frac{\partial W_1}{\partial z}, \qquad (8)$$

An analytical solution to eqn. (8) for a half-space was obtained in KPK-59 by the Laplace transform method. Here we use Wolfram's (1991) Mathematica, the NDSolve routine to solve eqn.(8) with the initial and boundary conditions:

$$W_1(0,t)=1,\quad W_1(z,t)0=1,\quad W(z,0)=W_0$$
$$D\frac{\partial W_1(c,t)}{\partial z}-uW_1(c,t)=0 \qquad (9)$$

Clearly, the boundary-value problems (8)-(9) describes redistribution of VMC by pure evaporation, with no infiltration.

For our experiment in (Fig. 1C) we had W(0,t)=0.18, W(z,0)=0.42, n=3.5 and k_s=0.0226 m/day. The most difficult soil characteristic is Indeed, all standard capillary pressure curves (Brooks-Corey, Van Genuchten, Fredlund, or others) as functions p(w) have almost vertical segments at very small phase saturations and at almost full saturations. The latter limit falls within the tension saturated conditions when a standard pressure plate apparatus or Penn State method for measuring p(w) are vulnerable to mistakes in determinations of the phase saturation w.

In order to get $p'(W_0)$ we used a pressure plate apparatus and obtained the capillary pressure P=ρ g [bar] (ρ = water density, g = gravity acceleration), which is shown in (Fig. 5) as a function of VMC (triangles).

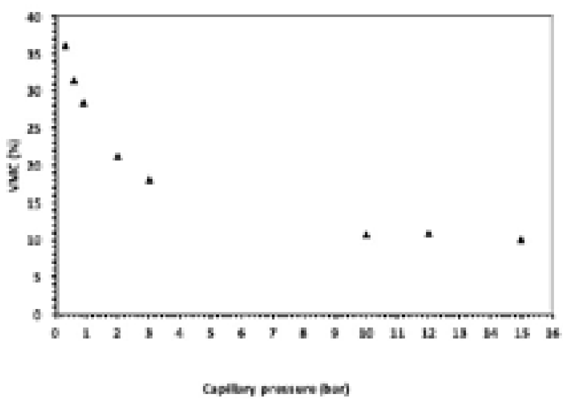

Figure 5. Water retention curve of block soil.

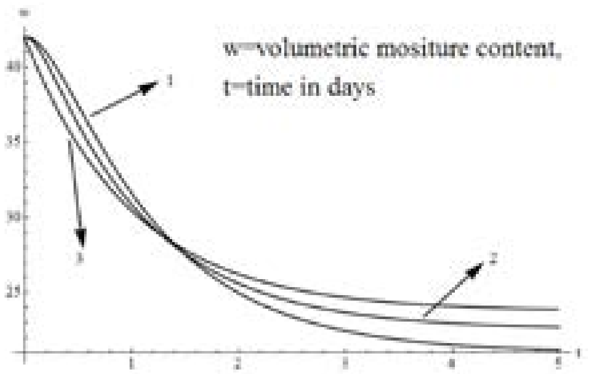

Figure 6. Modelled VMC as a function of time (in days) at the middle of the block.

We selected two points retrieved from (Fig. 4): p(0.36)=3 m and p(0.28)=9 m. Then we calculated a finite difference between these two points and calculated an approximate (extrapolated) value of p'(0.42)=50 m. This value was used in the computer algebra code. The results are shown in (Fig. 6) as W(0.1,t) (curve 1, time in days). For sensitivity analysis we also selected p'(0.42)=100 m (curve 2) and p'(0.42)=1000 m (curve 3). Curve 1 qualitatively matches the trend in (Fig. 3). For example, VMC at port 2 of (Fig. 2) in 3 days drops from 0.42 to 0.25 as shown on (Fig. 3a).

Figure 6 modelled VMC as a function of time (in days) at the middle of the block.

Unfortunately, we did not have a probe above probe 2 close to the soil surface that would give us the real rather than "extreme" (absolute dryness) moisture content at z=0.

Summary and conclusion

In hot deserts, and Oman is a typical example of this, low organic matter in sandy soils and limited fertilization of natural and cultivated vegetation are secondary bio-impeding factors, as compared with low VMC and high temperature in the root zone. Our experiments with green roofs prove this for extreme conditions, with no fertilization of the soil substrate for 5+ years and "smart irrigation" schemes. This paper studied an elementary cell of a 3-D cascade of a "smartly designed" soil, viz. a silt block with a sand sheath ("proppant") in contact with five faces of the block and its upper face open to solar radiation.

The conducted experiments with measurements of VMC within a block confirm that desiccation from full, post-ponding saturation to 3+ bars of capillary pressure is relatively rapid (within a month) during April-May in the Muscat area of Oman. A mathematical model of 1-D evaporation, based on the KPK-59 linearized transient Richards equation, gives qualitatively similar results. For advancement of the preliminary work in this paper we plan to measure the 3-D distribution of moisture content and temperature within desiccating blocks, using a dense network of probes. This will allow validation of the mathematical model.

This "normal" desiccation of the top-most blocks corroborates our hypothesis that the edaphic factor in general and "smart heterogeneity" of the soil substrate in particular are major controls of SWD and of hydroecology of natural and engineered plant environment in arid climates. Results of this study prove that a 3-D heterogeneity of soil physical properties, in particular, horizontal and vertical capillary barriers emerging on the interfaces between silt and sand generate eco-niches with stored soil water compartments favourable for lush vegetation in desert conditions.

The desiccation regime of the silt blocks is also important for local geotechnical engineering and catchment-scale management of water resources. Indeed, the soil making the studied block is a bed of a hydraulic structure (dam), which is one of the largest managed aquifer (MAR) recharge projects in Oman. When flash floods fill the dam reservoir, infiltration into the blocks is controlled by the degree of their dryness. Therefore, we can conclude that if the summer floods recur less frequently than once a month (this is just the case in Oman), then the MAR efficiency will not be affected by the "residual" wetness of silt in the top-most blocks.

Desiccation significantly increases the temperature in the blocks and re-wetting of the blocks reduces the daily average and peak temperatures, the latter by almost 15°C. This is extremely important for planning irrigation in smartly designed soil substrates and sustainability of wild plants in the region where the top soil peak temperature in the study area exceeds 70°C in summer but smartly structured soils maintain lash vegetation. Obviously, the layer of dry top-blocks already acts as a thermal insulator for the subjacent layers of wet blocks, which host the root zone of woody species. These plants cool the soil by both transpiration and shading, with minimal evaporation from the dry silty block surface. The details of temperature distribution in the blocks and heat fluxes there are needed to assess the thermal stress on the herbaceous species growing in the reservoir area, rooted in the top-most blocks in our system and perishing due to the soil dryness/extreme temperature and inability of the roots to penetrate to deeper wet block layers of the cascade in the heterogeneous pattern presented in this paper.

From the agronomic view point, the "smartly designed" soil substrate amalgamates the advantages of the fine and coarse texture but on a larger than usually perceived scale. Moreover, what is commonly illustrated as "cracked desiccated soil surface" in fear-mongering of desertification and propaganda of global warming can —with a smart engineering design—be an excellent agronomic technique leading to drastic increases of water use efficiency. The recipe is very simple: backfill the cracks by a coarse "proppant" and make a cascade of 3-D elementary cells as presented in this paper.

Natural soils in Oman are mostly sandy and correspondingly, the natural vegetation is ecologically adopted to the adverse ambient conditions through drought deciduousness, reduced size of the leafs and limited biomass production. This is not suitable for desert farming and shading of tropical buildings by ornamental plants. Juxtaposition of structurally contrasted blocks and sandwiched "proppants" solves the problem: with limited water resources for irrigation, the block-"proppant" composite of relatively rapidly infiltrates the irrigation water (common in sandy soils) and, on another hand, minimizes intensive evaporation (common in silty-clayey soils). The temperature regime within the silty blocks, even of the topsoil array in the "smart" cascade remains tolerable for the plants, until this array gets dry.

Some of the results in this paper were presented to the 10th International Conference on Thermal Engineering: theory and application held in Muscat on February 26-28, 2017 as Kacimov, A., Al-Maktoumi, A., Al-Ismaily, S., Obnosov, Y. and Al-Busaidi, A. Evaporation and heat convection through a "smartly designed" structured topsoil.

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