EVAPORATION AND HEAT CONVECTION THROUGH A “SMARTLY DESIGNED” STRUCTURED TOPSOIL

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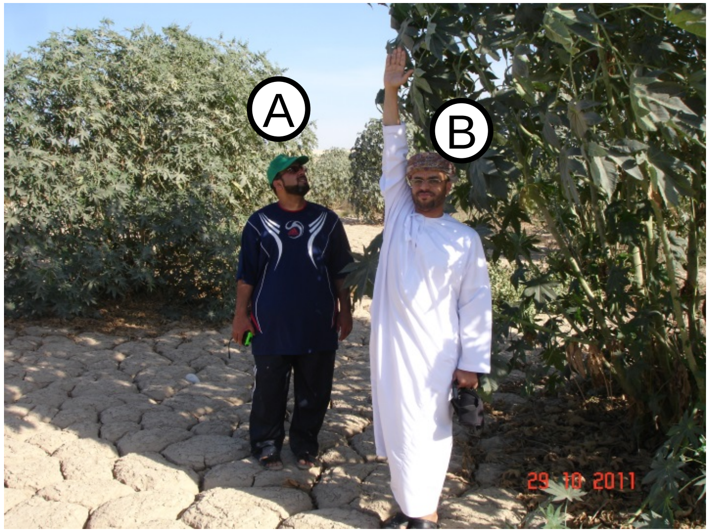

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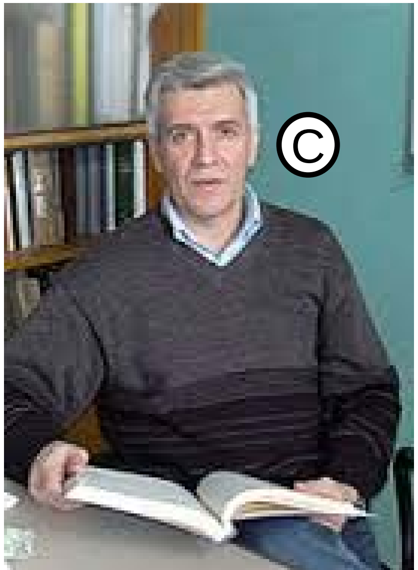

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Plan of Presentation:

“Drought makes people more creative”
Don Cameron, Californian farmer

Key words: *desiccation, evaporation, soil layering, unsaturated conductivity*

1. Agricultural motivation for heat and moisture transfer in structured soils

2. Experiments with desiccating silt-sand composites

3. Modeling (analytical +CFD) of moisture transport and heat convection

- Transient desiccation of an initially saturated homogeneous soil

- Transient heat advection in a homogeneous soil

- Steady evaporation through a mulched soil

4. Conclusions

1. Motivation

Soil- water-heat-vegetation in Oman:

Cultivated land=80,000 ha
(out of 315,000 km^2 of total country area)

Ornamental plants for thermal insulation of local buildings from caustic insolation.

Climate: arid – hyperarid: P=50-250 mm/year, E=1500-3000 mm/year, $3<ET_0<10$ mm/day, T_{av}=30-35 C^o, $T_{top\ soil}$ =70+ C^o
Daily mean global radiation flux, F, in May (Batinah): 808 W/m^2
April-August F>600 W/m^2 , RH (av) =49%

Very limited fresh surface water: annual renewable water resources = 1300 mln m^3, 80% of P is converted to ET

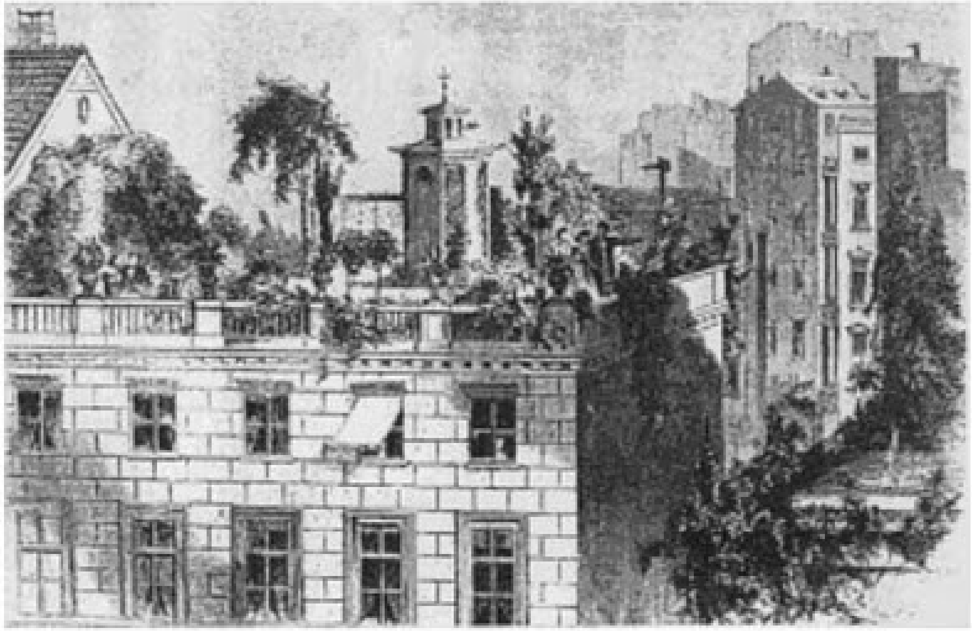
Monthly Air Conditioning bill in June
(my house): 50-75 US$/month
(>70% of electricity bill)
Building sector consumes 40% of energy

Oman 1971-2006: population tripled;
energy supply increased 20 times

CURRENT STRATEGY

- fighting for food security
- war for water use efficiency (WUE),
- battle with extreme heat stress on open-air crops
- confronting huge energy consumption in air-conditioned buildings and greenhouses
- combatting secondary soil salinization

Fancy extensive green-roofs



C. Rabitz, "Naturdächer von vulkanischem Cement ", 1867 (Germany)

Modern dacha
roof garden

Shading building envelopes by smartly-designed soil substrates and capillary irrigation

Fracking of tight rocks (pays and coalbeds)

USSR (1950-s):

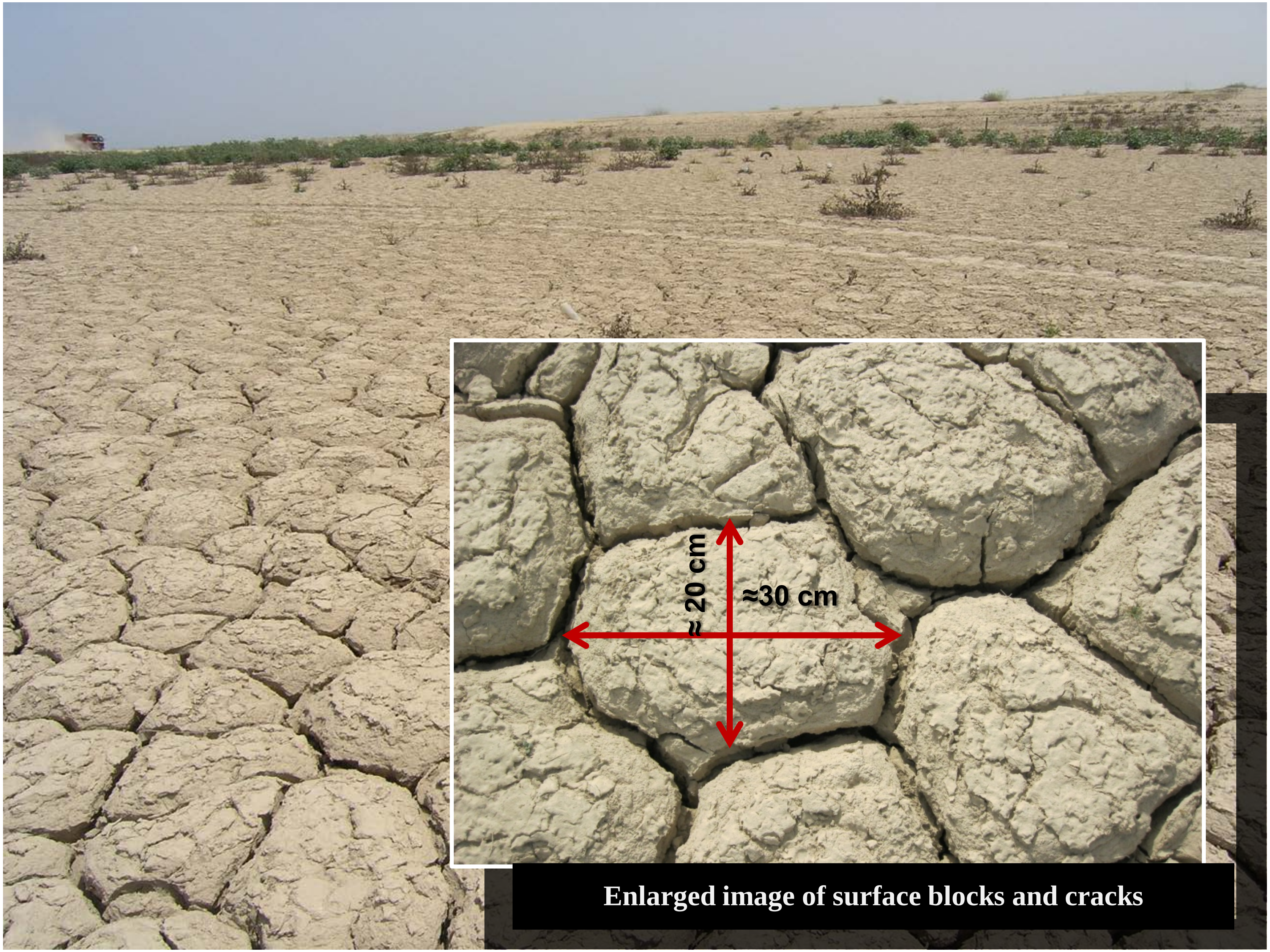
Khristianovich-Zheltov and Barenblatt-Kazemi block-fracture models

Crux:

- Engineered heterogenization of the pay
- Complex topology of fluids’ fluxes
- Juxtaposition of   a) Darcian resistance, b) capillarity, c) gravity, d) exerted dynamic pressure

In topsoils: evapotranspiration

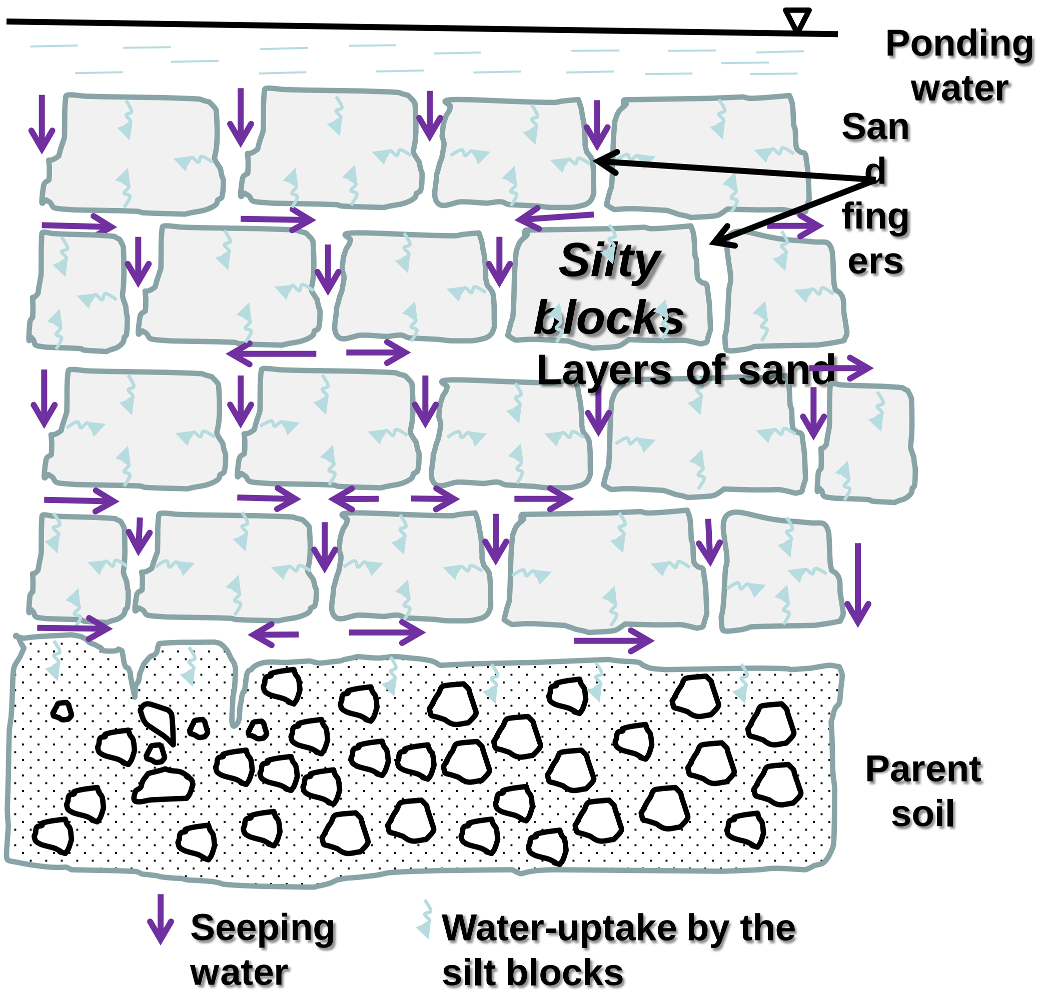
Ak-Khod dam: routine dry reservoir bed and propaganda in drought fearmongering

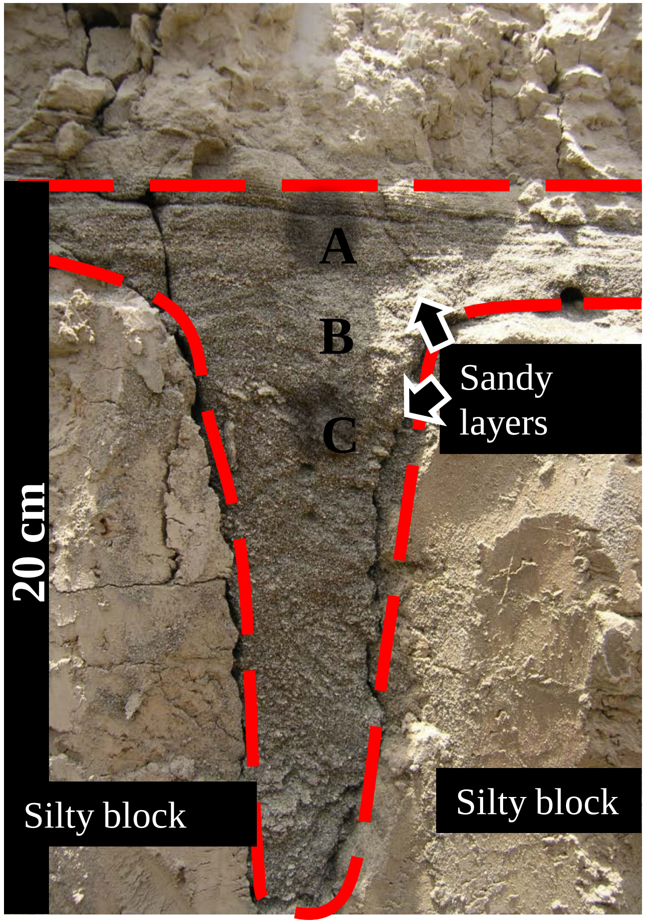


Enlarged image of surface blocks and cracks

2. Experiments

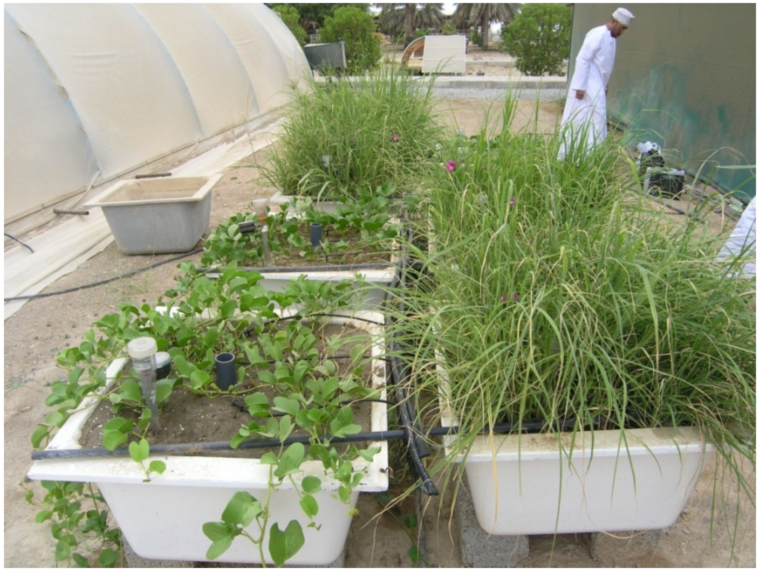
Smart structural design in Nature (Al-Khod dam reservoir bed): blocks-proppant filled fractures





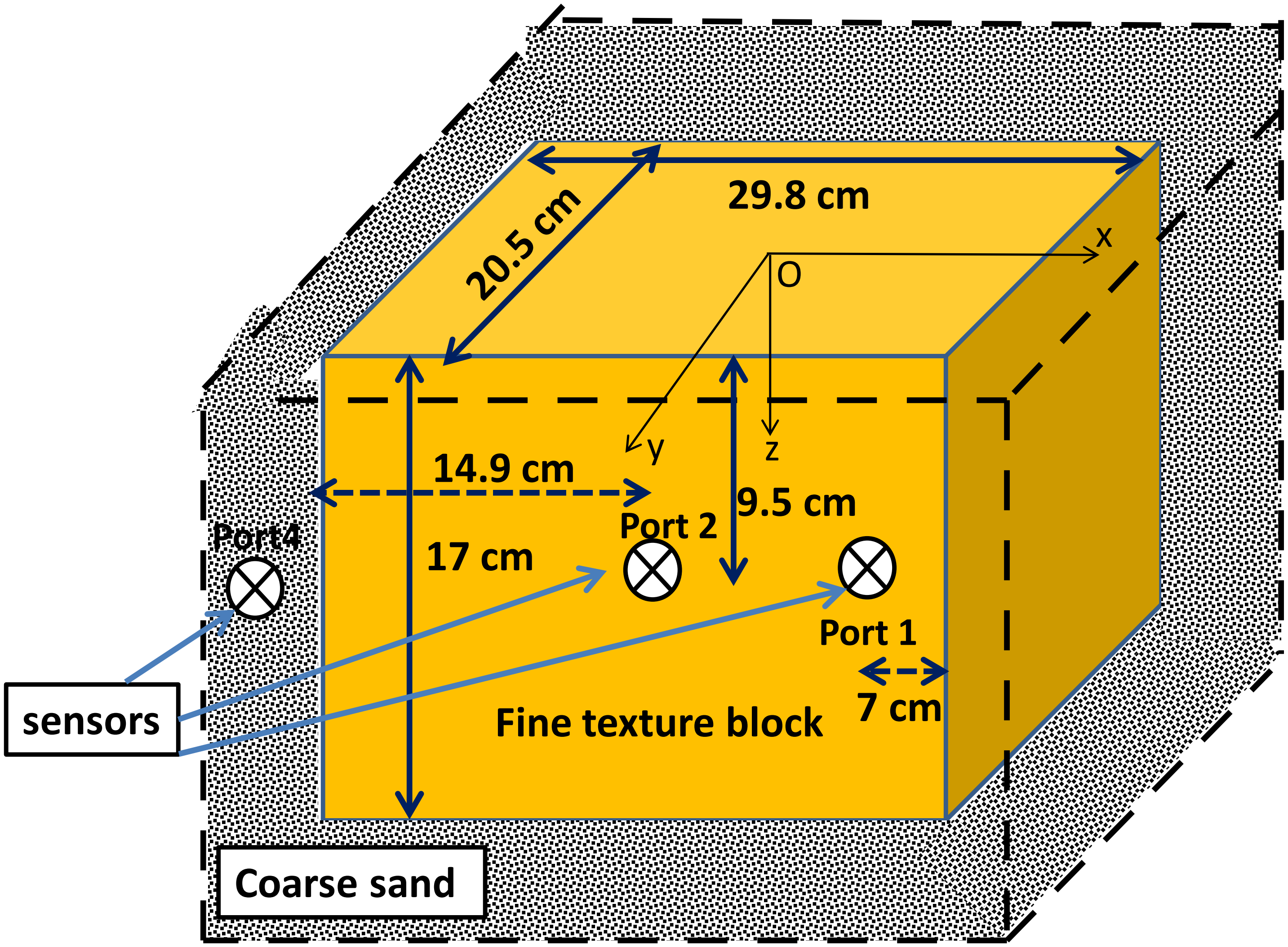
Hydrological Sciences J., 2013.
J. Arid Land, 2014.
J. Hydrol. Eng., Amer. Soc. Civil Eng., 2015.
Transport in Porous Media, 2015.
Arabian J. Geosciences, 2016
Water Resour Res., 2016
J. Agricultural Sci., 2017

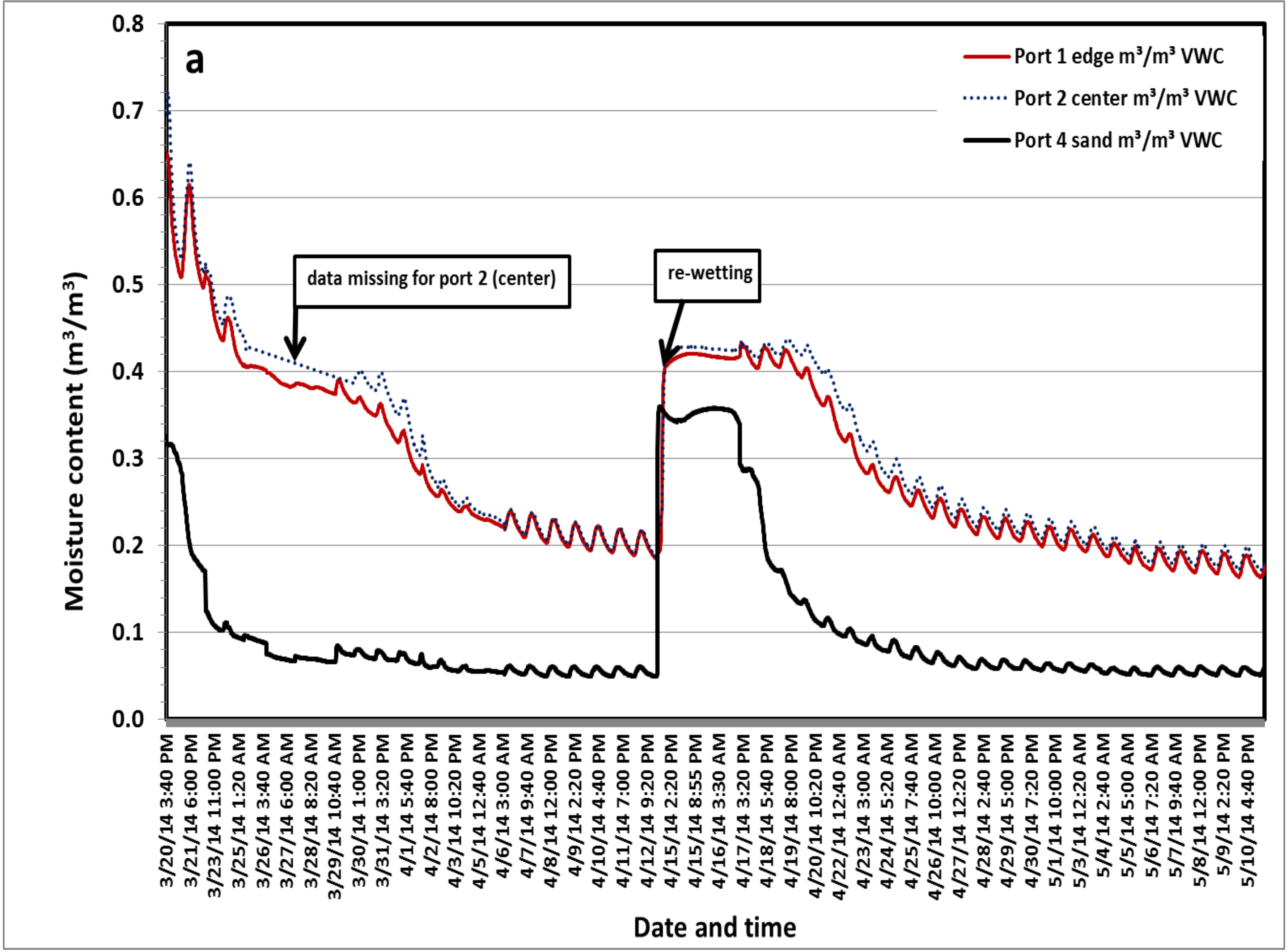
Mimicking Nature: substrate design in farm experiment with engineered block-proppant structured soil substrate



Fluids' fluxes are fascinatingly intricate, analogous to GOGD in tertiary EOR

Desiccation of a saturated block:
Thermometry and moisture content recording
March 20-May 10, 2014


29.8 cm
20.5 cm
x
O
y
z
14.9 cm
9.5 cm
Port 2
Port4
17 cm
Port 1
7 cm
sensors
Fine texture block
Coarse sand


a
Port 1 edge m³/m³ VWC
Port 2 center m³/m³ VWC
Port 4 sand m³/m³ VWC
data missing for port 2 (center)
re-wetting
Moisture content (m³/m³)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
3/20/14 3:40 PM
3/21/14 6:00 PM
3/23/14 11:00 PM
3/25/14 1:20 AM
3/26/14 3:40 AM
3/27/14 6:00 AM
3/28/14 8:20 AM
3/29/14 10:40 AM
3/30/14 1:00 PM
3/31/14 3:20 PM
4/1/14 5:40 PM
4/2/14 8:00 PM
4/3/14 10:20 PM
4/5/14 12:40 AM
4/6/14 3:00 AM
4/7/14 9:40 AM
4/8/14 12:00 PM
4/9/14 2:20 PM
4/10/14 4:40 PM
4/11/14 7:00 PM
4/12/14 9:20 PM
4/15/14 2:20 PM
4/15/14 8:55 PM
4/16/14 3:30 AM
4/17/14 3:20 PM
4/18/14 5:40 PM
4/19/14 8:00 PM
4/20/14 10:20 PM
4/22/14 12:40 AM
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4/30/14 7:20 PM
5/1/14 10:00 PM
5/3/14 12:20 AM
5/4/14 2:40 AM
5/5/14 5:00 AM
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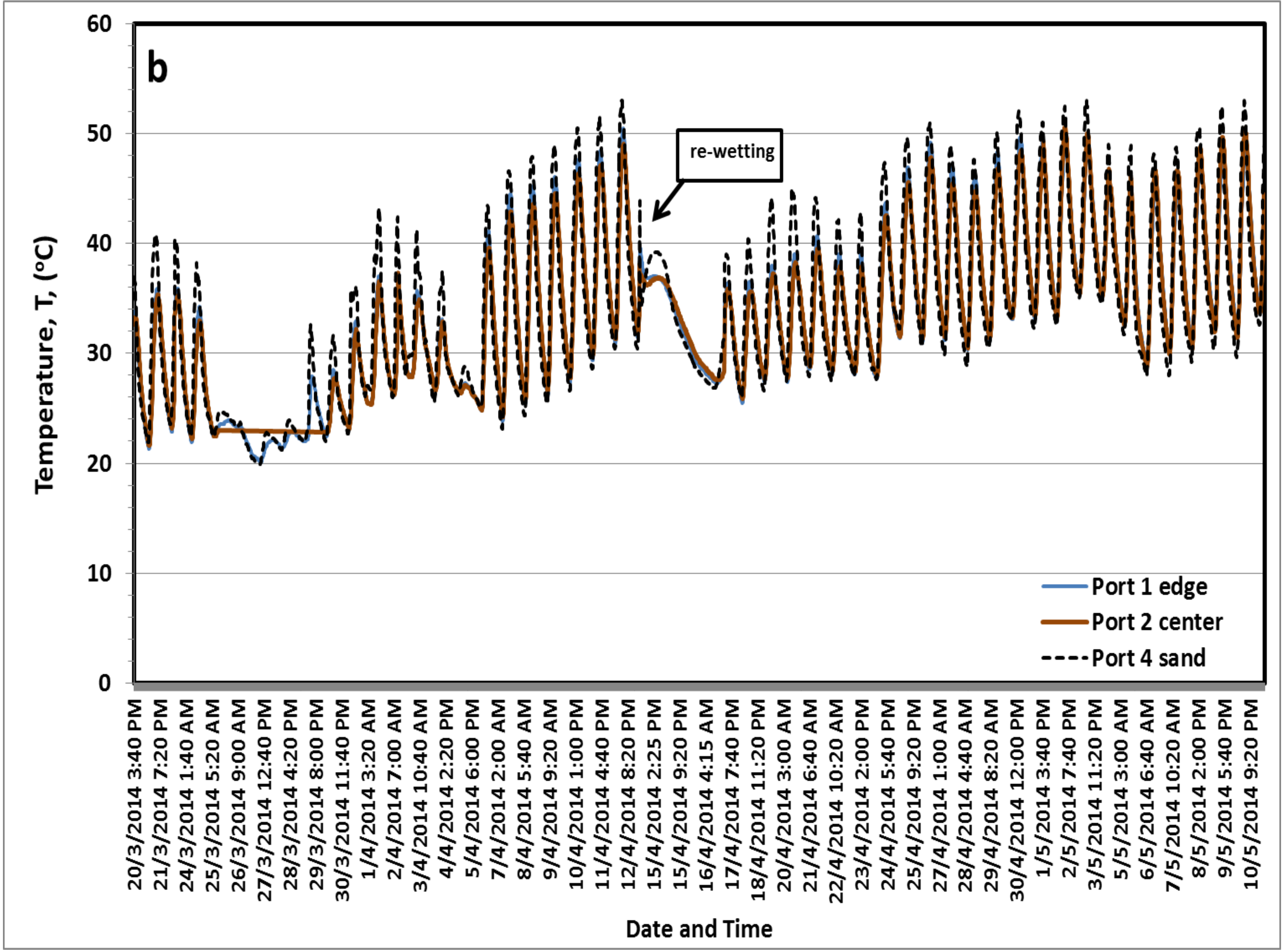
5/9/14 2:20 PM
5/10/14 4:40 PM
Date and time


b
re-wetting
Temperature, T, (°C)
60
50
40
30
20
10
0
Port 1 edge
Port 2 center
Port 4 sand
20/3/2014 3:40 PM
21/3/2014 7:20 PM
24/3/2014 1:40 AM
25/3/2014 5:20 AM
26/3/2014 9:00 AM
27/3/2014 12:40 PM
28/3/2014 4:20 PM
29/3/2014 8:00 PM
30/3/2014 11:40 PM
1/4/2014 3:20 AM
2/4/2014 7:00 AM
3/4/2014 10:40 AM
4/4/2014 2:20 PM
5/4/2014 6:00 PM
7/4/2014 2:00 AM
8/4/2014 5:40 AM
9/4/2014 9:20 AM
10/4/2014 1:00 PM
11/4/2014 4:40 PM
12/4/2014 8:20 PM
15/4/2014 2:25 PM
15/4/2014 9:20 PM
16/4/2014 4:15 AM
17/4/2014 7:40 PM
18/4/2014 11:20 PM
20/4/2014 3:00 AM
21/4/2014 6:40 AM
22/4/2014 10:20 AM
23/4/2014 2:00 PM
24/4/2014 5:40 PM
25/4/2014 9:20 PM
27/4/2014 1:00 AM
28/4/2014 4:40 AM
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6/5/2014 6:40 AM
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8/5/2014 2:00 PM
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Date and Time

3. Modeling

Desiccation (moisture transport)

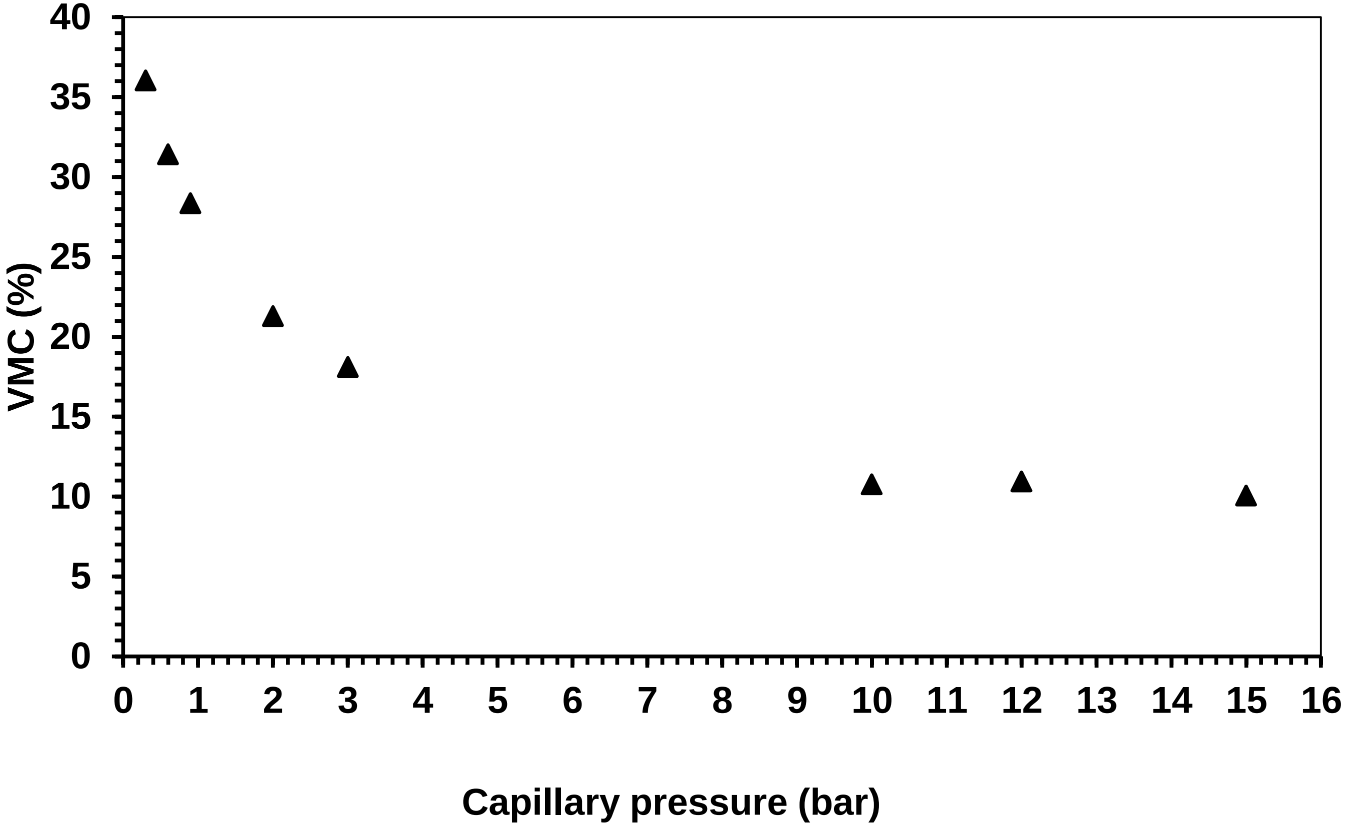
The Richards’ equation for a 3-D distribution of volumetric moisture content, $\theta(x,y,z,t)$ [unitless], and pressure head, $p(x,y,z,t)$ [m], inside the silt block reads:

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

Unsaturated (weting phase) hydrualic conductivity :

$$k(W)=k_s\left(\frac{\theta-\theta_r}{\theta_s-\theta_r}\right)^n=k_sW^n$$

Measured capillary pressure function



Perturbation method:

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

$$k(W) = k_s W_0{}^{n} + \lambda n k_s W_0{}^{n-1} W_1(x,y,z,t),$$

$$p(W) = p(W_0) + \lambda p'(W_0) W_1(x,y,z,t),$$

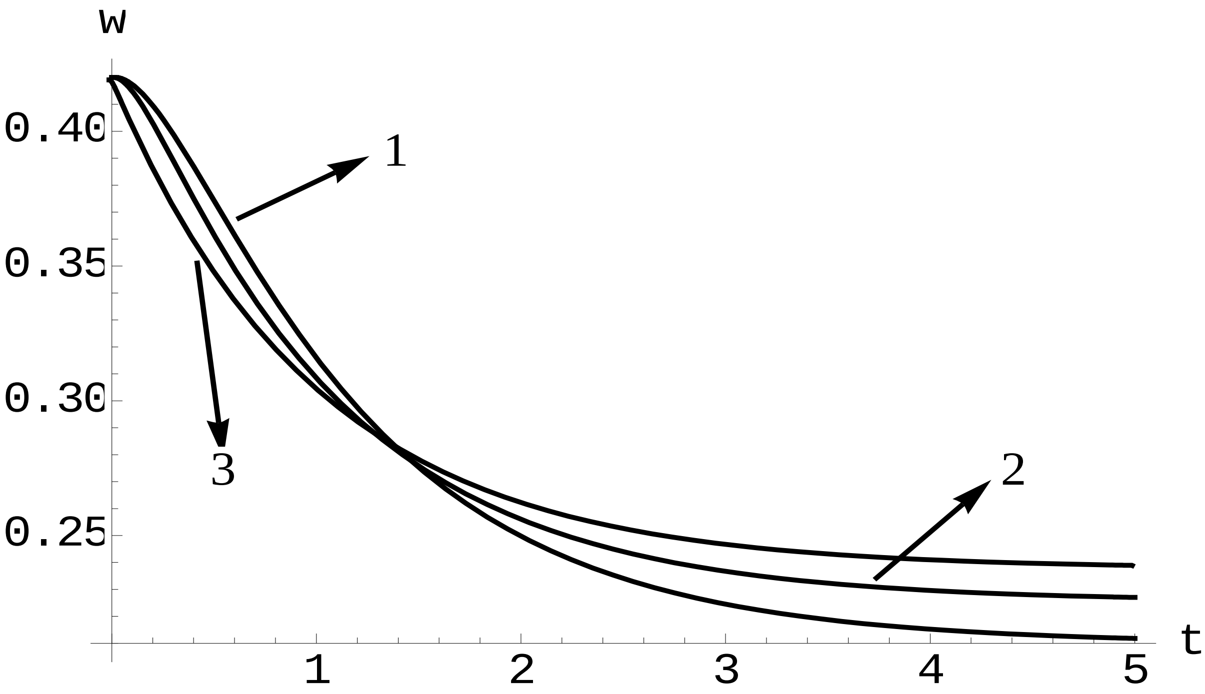
1-st order approximation:

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

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

1-D evaporation, initial and boundary conditions:

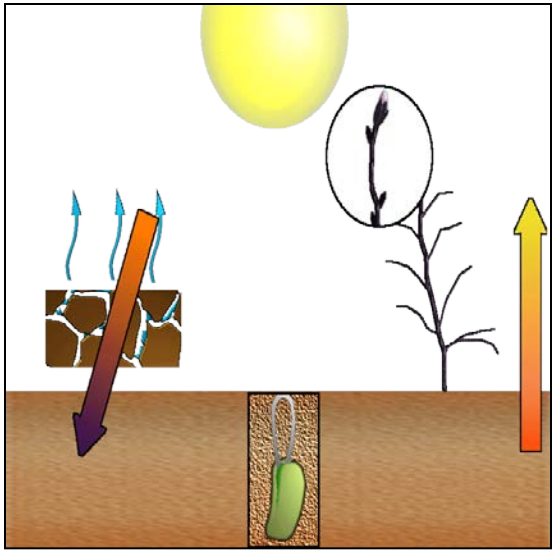
$$W_1(0,t)=1, W_1(z,0)=1, W(z,0)=W_0, \qquad D\frac{\partial W_1(c,t)}{\partial z} - uW_1(c,t)=0$$

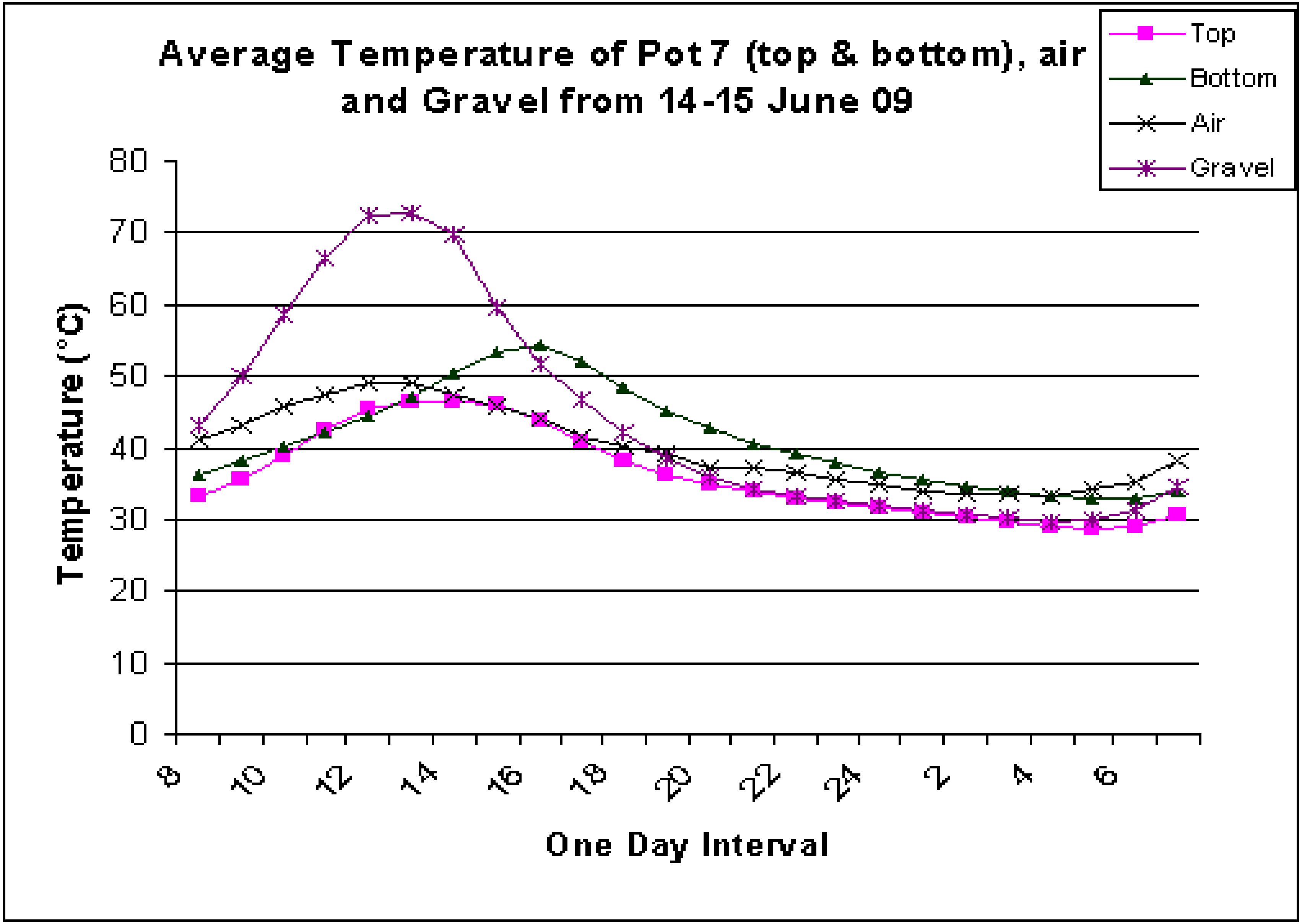


Moisture content in the middle of the block (curve 1) for the capillary pressure curve: *p*(0.36) =3 m and *p*(0.28) =9 m, *p’*(0.42)=50 m.

Sensitivity analysis: *p’*(0.42)=100 m (curve 2) and *p’*(0.42)=1000 m (curve 3).

Seed	**Temperature (°C)**		
	Minimum	**Optimum**	**Maximum**
Maize	8-10	32-35	40-44
Rice	10-12	30-37	40-42
Wheat	3-5	15-31	30-43
Barley	3-5	19-27	30-40
Rye	3-5	25-31	30-40
Oats	3-5	25-31	30-40
Buckwheat	3-5	25-31	35-45
Bindweed	0.5-3	20-35	35-40
Tobacco	10	24	30




Average Temperature of Pot 7 (top & bottom), air and Gravel from 14-15 June 09

1-D heat transfer governing equation

$$\frac{\partial(C_p T)}{\partial t} = \frac{\partial}{\partial z}\left[\lambda(\theta)\frac{\partial T}{\partial z}\right] - C_w \frac{\partial(q_w T)}{\partial z}$$

$$\lambda(\theta) = \lambda_0(\theta) + \beta C_W \,|\, q_w \,| -$$

apparent thermal conductivity of unsaturated soil

$$\lambda_0(\theta) = b_1 + b_2\theta + b_3\sqrt{\theta} -$$

effective thermal conductivity of unsaturated soil

Conductive Heat Flux (W m^{-2})

$q_h = -\lambda(\theta)\, dT/dz$

λ= thermal conductivity (W m^{-1} K^{-1})

= 0.0256 for dry air

= 0.6 for water

= 0.92 for clay

= 0.298 for sand

Assumptions:

- No vapour flow/diffusion
- No roots
- Homogeneous soil

$$C_p = (1-\theta_s)C_{solid} + \theta C_w + (\theta_s - \theta)C_a$$

volumetric heat capacity of soil

$$C_W = 4.18\ 10^6 \frac{J}{m^3 C^o} -$$

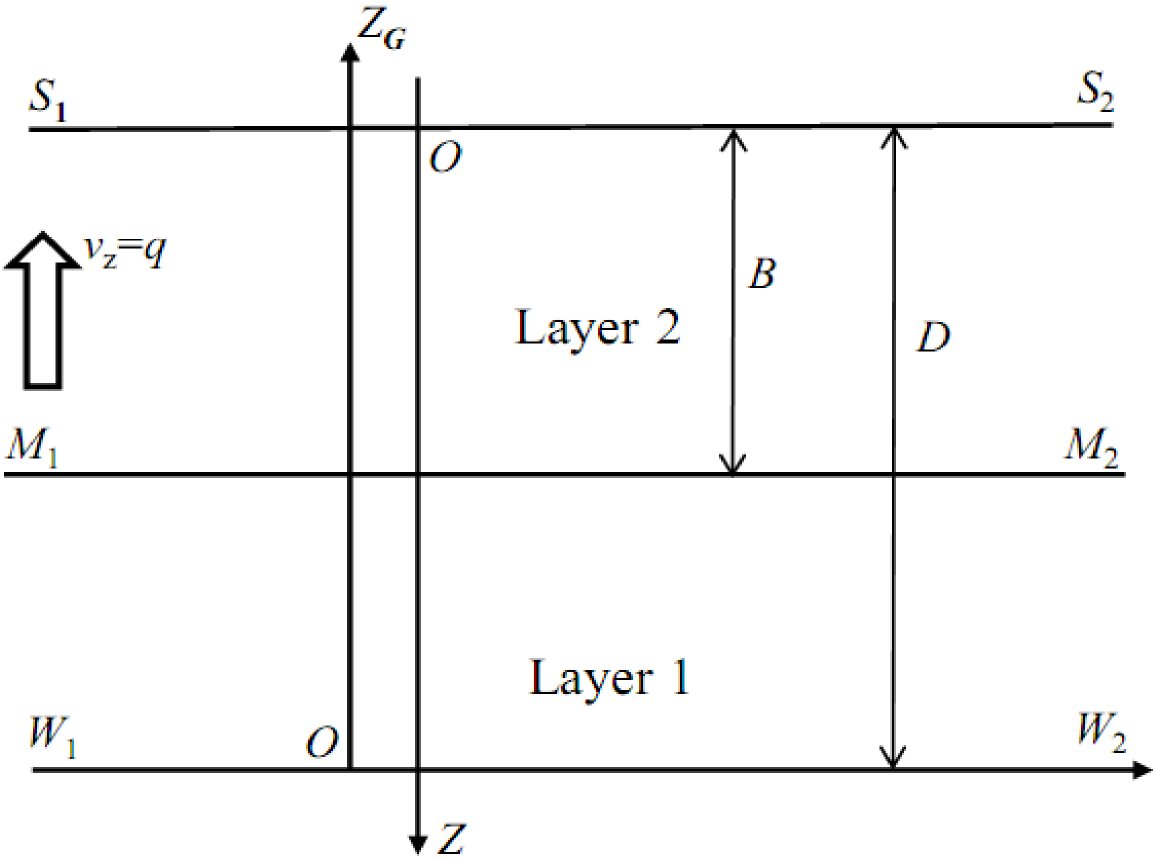
volumetric heat capacity of water

$$C_{solid} = 1.92\ 10^6 \frac{J}{m^3 C^o} -$$

volumetric heat capacity of soilid grains

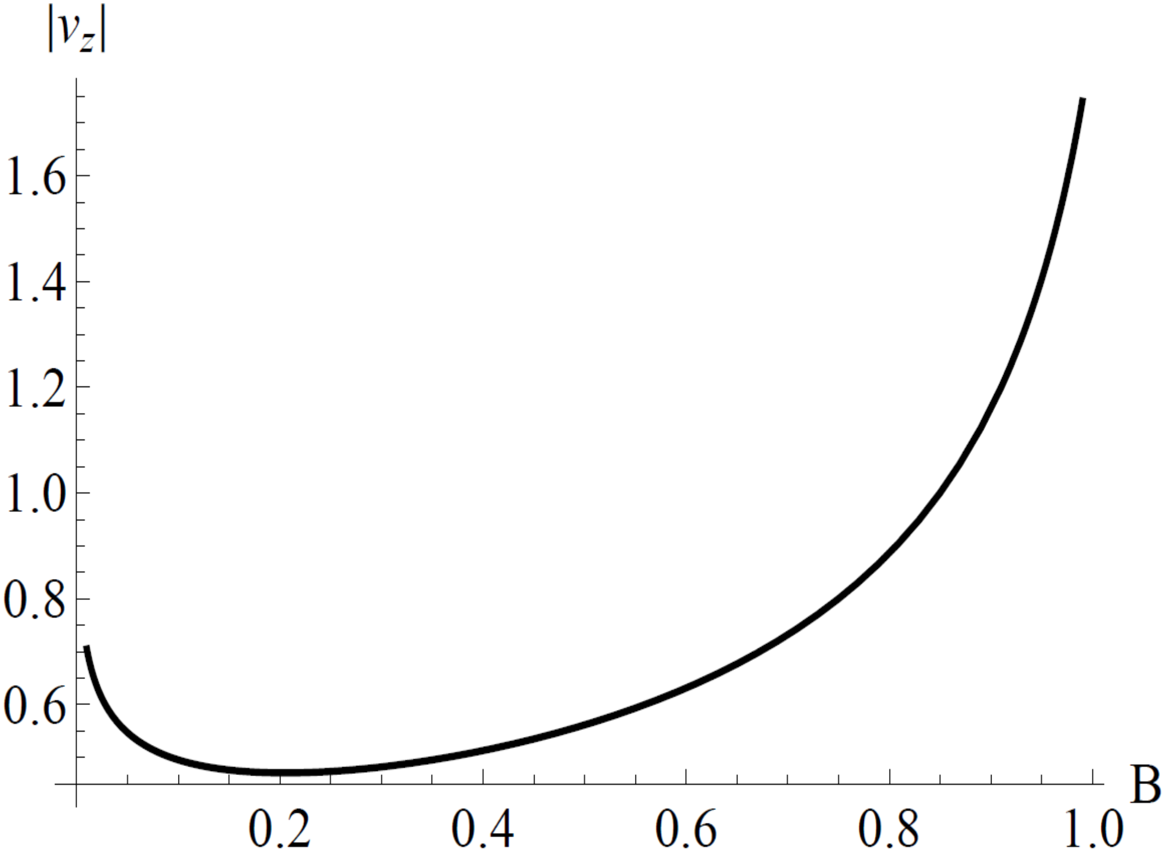
Analytical modeling of 1-D evaporation in 2-layered soil

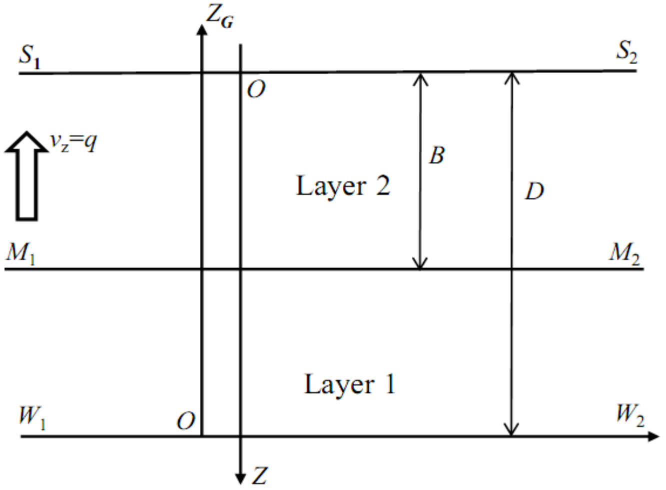
$$v_{1Z} = -k_1(p_1)\frac{dp_1}{dZ} + k_1(p_1), \quad v_{2Z} = -k_2(p_2)\frac{dp_2}{dZ} + k_2(p_2) \qquad (1)$$



Gardner’s exponential soil:

$$k_1(p_1) = K_1 \exp[\alpha_1\ p_1], \quad k_2(p_2) = K_2 \exp[\alpha_2\ p_2],$$





Dimensionless evaporative flux $|v_z|$ as a function of B for a coarse upper layer: K_2=100, α_2=4, α_1=0.4 and p_{2s}=-*infinity*.

Gardner’s algebraic soil:

$$k_1(\mathrm{p}_1) = \frac{a_1}{S_1^{n_1} + b_1} = \frac{K_1}{S_1^{n_1} / b_1 + 1},$$

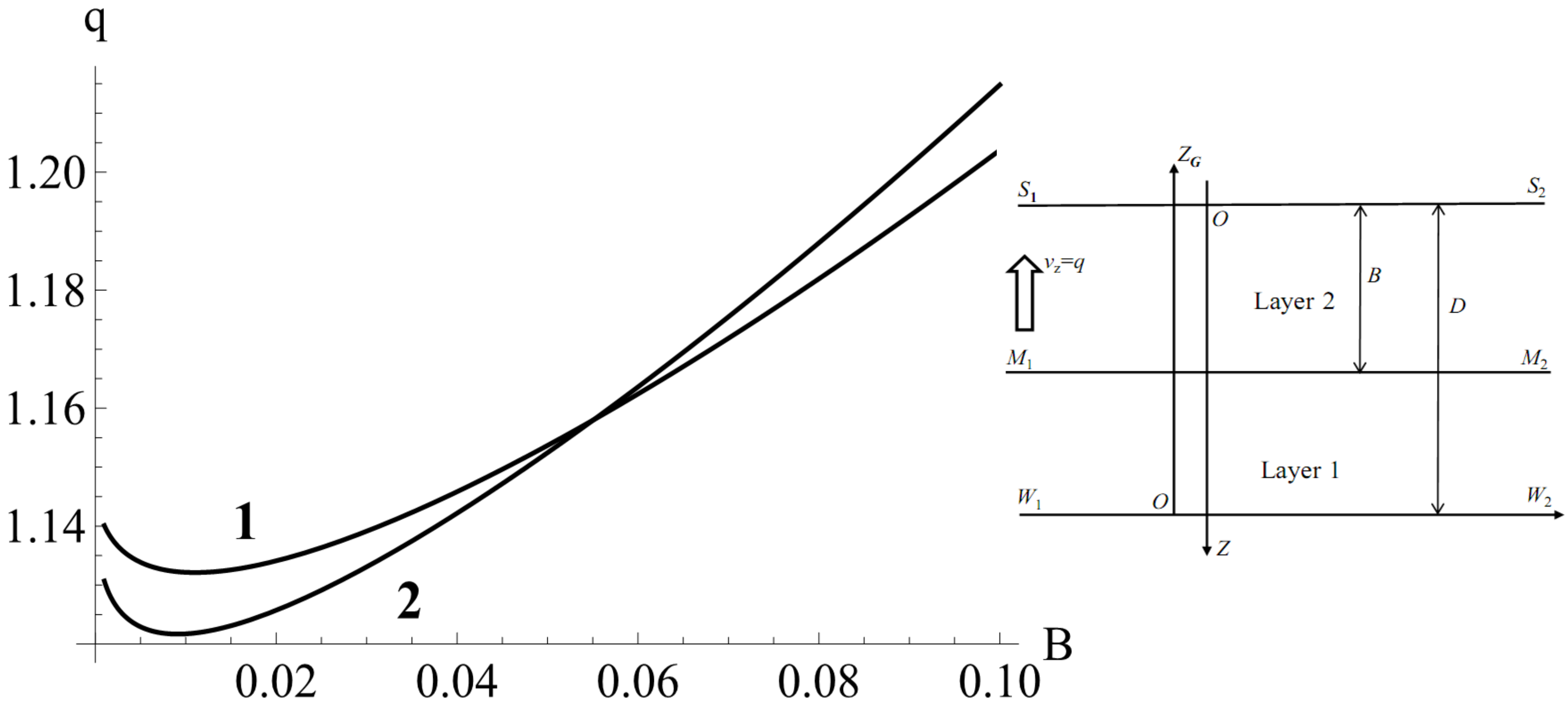
$$k_2(\mathrm{p}_2) = \frac{a_2}{S_2^{n_2} + b_2} = \frac{K_2}{S_2^{n_2} / b_2 + 1},\ \mathrm{S}_{1,2} = -\,\mathrm{p}_{1,2} \qquad (2)$$

Analytical solution:

$$Z_G(S_1) = \frac{S_1}{1+q}\,\mathrm{F}\left[1, 1/n_1; 1+1/n_1; -\frac{qS_1^{n_1}}{b_1 + b_1 q}\right], \quad 0 < Z_G < 1-B, \quad 0 < \mathrm{S}_1 < \mathrm{S}_{1B},$$

$$Z_G(S_2) = 1 - B + \frac{K_2}{K_2+q}\left(S_2\,\mathrm{F}\left[1, \frac{1}{n_2}; 1+\frac{1}{n_2}; \frac{-qS_2^{n_2}}{b_2(K_2+q)}\right] - S_{1B}\,\mathrm{F}\left[1, \frac{1}{n_2}; 1+\frac{1}{n_2}; \frac{-qS_{1B}^{n_2}}{b_2(K_2+q)}\right]\right),$$

$$1 - B < Z_G < 1, \quad S_{2B} < S_2 < S_S,$$



Evaporation rate $q(B)$ for D=20 cm. Layer 1 is Yolo clay: $n_1=2$, a_1 =400cm^3 /day, b_1 =400cm^2, K_1=1cm/day and Layer 2 is Pachapa sandy loam: $n_2=3$, a_2 =3.2·10^{5}cm^4/day, b_2=2,6·10^{4}cm^3, K_2 =12.3 cm/day (curve 1).Layer 1 is Yolo clay and Layer 2 is Willis' sand: n_2=4, a_2 =1.7·10^{8}cm^4/day, b_2 =2.6·10^{6}cm^3, K_2 =68 cm/day (curve 2).

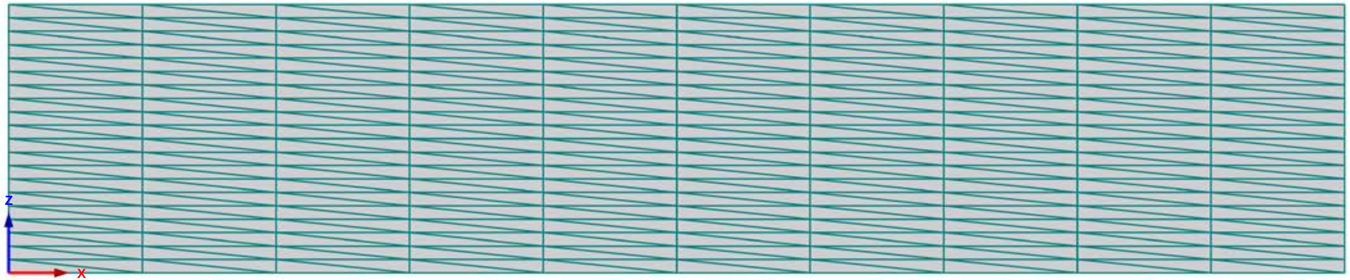
HYDRUS2D modeling

Upper layer: sand (K_s= 712 cm/day)
Lower layer: silty clay (K_s= 0.48 cm/day)

X=100 cm
Z=20 cm

Soil characteristics:
Van Genuchten model

p=-10000 cm



p=0 cm

FEM mesh:11 nodes in x direction, 21 nodes in z-direction

q_{min} =0.041 cm/day (6 rows of upper nodes – sand)
q =0.07 cm/day (2 rows of upper nodes – sand)
q =0.055 cm/day (10 rows of upper nodes – sand)

Project 2-layered corase mesh-temperature
FE-Mesh

4. Conclusions

Simple but smart agroengineering heterogenization of soil substrate results in:

- Reduced evaporation of irrigation water
- Mitigated thermal stress on plant roots
- Novel and aesthetically beautiful mathematical models/solutions

“Millions of pounds are spent on research and development of ‘Advanced Technologies’ – advancing them further and further from any relevance to the majority of the world. We believe that we must research and develop those ***‘simpler’*** *but not unadvanced technologies, which the majority of the people in the Third World use and live within.”*

Mr. Cain

"All-Mighty said: all what is complicated is not necessary and all what is necessary is SIMPLE"

M.Kalashnikov

"There is a master key to success with which no man can fail. Its name is SIMPLICITY … reducing to the simplest possible terms every problem."

Sir Henry Deterding