Control of Topology of Water Fluxes in Arid Agriculture: Amalgamation of Subsurface Irrigation, Managed Aquifer Recharge and Engineered Soil Substrate

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Plan of Presentation:

"Drought makes people more creative"
Don Cameron, Californian farmer

Key words: fracking, proppant, capillary barrier, "dry dams", optimal structural design, subsurface irrigation, Riesenkampf-Philip's theories revisited

1.Facts about agriculture and groundwater in Oman

2. Main idea: analogy with fracking and gas-oil gravity drainage (GOGD)

3. Main discovery of "smart" sediment structure in MAR reservoirs of "dry dams"

4. Mimicking Nature in designed soil substrates with subsurface and capillary syphoning irrigation

5. Novel mathematical solutions fos subsurface emiters: line and point sources

6. Conclusions

1. Agriculture and GW in Oman

No fresh surface water

All irrigation water in agriculture comes from groundwater:
- Tube wells+Aflaj (springs and horizontal wells)

Climate: arid - hyperarid (P=50-250 mm/year, E=1500-3000 mm/year, $3<ET_0<10$ mm/day)

1 acre-foot=1233.5 m^3

Plethora of solar radiation (up to 1100 watt/m^2)

Annual renewable water resources = 1300 mln m^3, 80% of P is converted to ET, 15 % - natural aquifer recharge, 5% - runoff to ocean (the main source of MAR)

NATIONAL STRATEGY: food and water security

MAIN PROBLEMS:

- war for water use efficiency (WUE),
- battle with extreme heat stress on open-air crops,
- confronting huge energy consumption in air-conditioned greenhouses,
- combatting secondary soil salinization,
- fighting against depletion of aquifers/sea water intrusion

Annual per capita of renewable fresh water =500 m^3

Cultivated land=80,000 ha (out of 310,000 km^2 of total country area); same attacks on agriculture: <2% of GDP, low employment capacity, low prestige,.

National fresh water deficit=300 mln m^3/year

Irrigation: border-flood, furrow, modern (drip-bubbler-sprinkler)

Main crops: date palms, banana, tomato, mango, water melon, alfa-alfa, Rhodes grass, …

Legal national constraints on well drilling; national program of monitoring of drawdowns, soil and groundwater salinity

Huge quantities of "production water": 1 barrel of crude generates 9 barrels of brackish-saline-brine "aquifers" water

2. 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

We added: plant roots (transpiration), evaporation, "target fluid" - renewable (water)

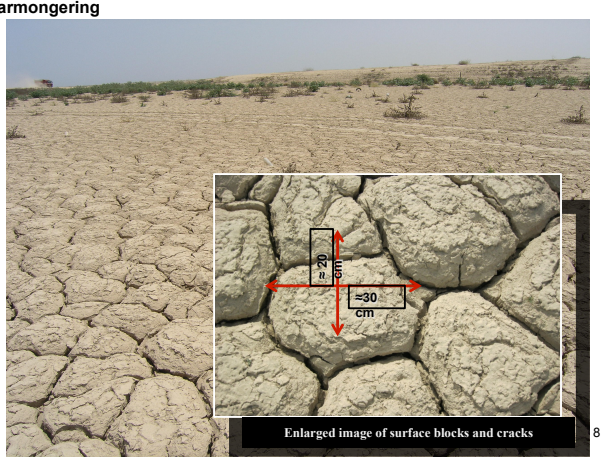
3. Discovery

MAR (storm flow banking in unconfined aquifers) via recharge dams Oman: 45 dams (as of 2015)

Ak-Khod and Wadi Dayka dams in Oman

7

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



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Ak-Khod dam: lush vegetation in some areas of dry reservoir bed (water table deep!)

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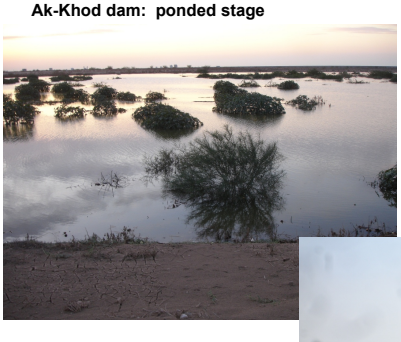
Ak-Khod dam: ponded stage



Root flooding - roots' topology

- Castor oil plant
- Christ thorn tree
- Ghaf tree
- Acacia

Ak-Khod dam: soil studies (tens of pedons +coring)

11

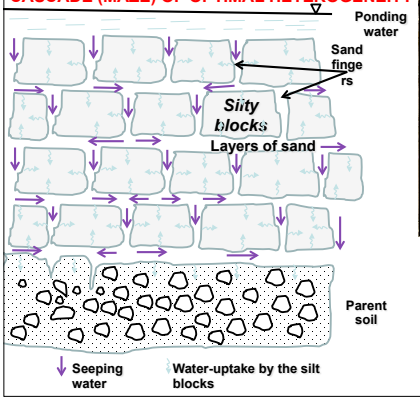
Ak-Khod dam: wadi flow current metering and suspended sediment load measurements

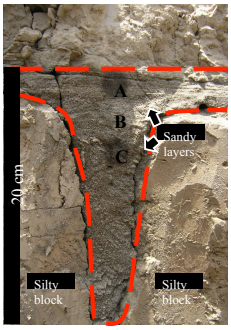
EUREKA!

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

NOT A ROUTINE SOIL LAYERING!

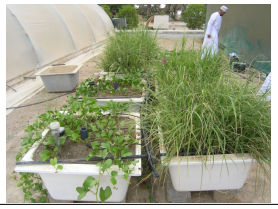
CASCADE (MAZE) OF OPTIMAL HETEROGENEITY





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.

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

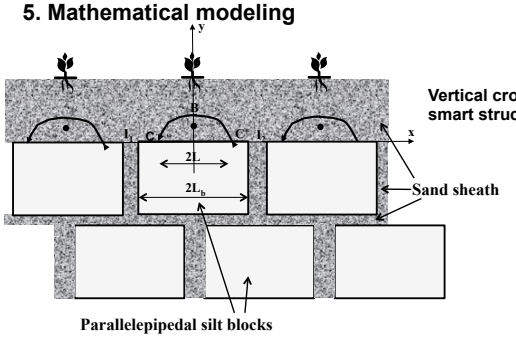


Fluids' fluxes are fascinatingly intricate,
ANALOGOUS to GOGD in tertiary EOR

Wifes cultivating smartly designed and regular home gardens

Capillarity: irrigation by siphoning versus capillary barriers in block-proppant soil substrates (ornamental plants, LAI)

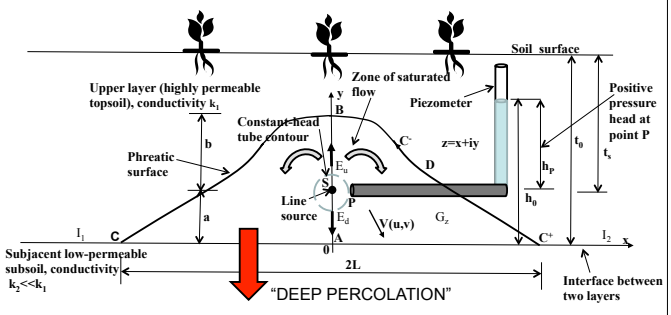
5. Mathematical modeling



Vertical cross-section of a smart structure

Retrieved form D. Reich, R. Godin, J.L. Chávez, I. Broner
http://www.ext.colostate.edu/pubs/crops/04716.html/

Vertical cross-section: one block, one emitter

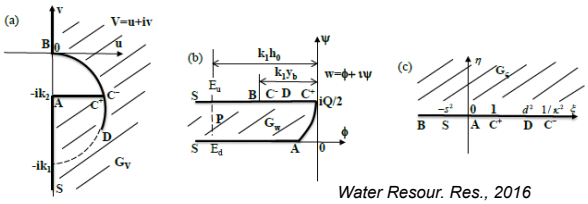


- Is the size $2L$ of the wetted zone compatible with a horizontal size $2L_b$ of the block?
- How much seeps into the substratum and evaporates, depending on a, k_1,k_2?
- What is the shape of the free surface, especially, the elevation b of the "bulb" apex?
- What is the flow topology for an emitter in a finite-thickness soil layer evaporating/ infiltrating at the top and underlain by a water table?

Boundary-value problem

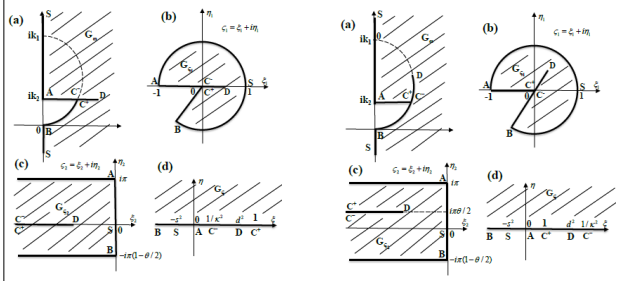
w(z), complex potential is a holomorphic function

$$SB:\psi = Q/2, \quad x = 0$$
$$SA:\psi = 0, \quad x = 0$$
$$AC^+:\psi = k_2 x, \quad y = 0$$
$$BDC^+:\psi = Q/2, \quad \phi + k_1 y = 0$$



Water Resour. Res., 2016

Two flow regimes



Final solution:

$$x(\xi) = \frac{Q}{2k_2} - \frac{Q\sin\pi\alpha(1-\theta)}{4\pi\sqrt{k_1 k_2}\cos\pi\alpha}\,\mathrm{Im}\{(\kappa-1)J^+(\xi,\theta)+(\kappa+1)J^+(\xi,2-\theta)\}$$

$$y(\xi) = \frac{Q\sin\pi\alpha(1-\theta)}{4\pi k_1\sqrt{1-k}\cos\pi\alpha}\,\mathrm{Im}\{(\kappa-1)J^-(\xi,\theta)+(\kappa+1)J^-(\xi,2-\theta)\}$$

where

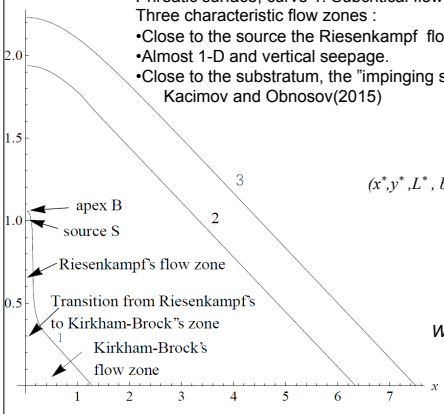
$$J^\pm(\xi,\theta) = \mathrm{j}(\xi,\theta) \pm \mathrm{j}(\xi,-\theta)$$

$$\mathrm{j}(\xi,\theta) = \frac{e^{i2\pi\alpha}}{1+\theta/2}\left(\frac{\sqrt{\xi}-1}{\sqrt{\xi}+1}\right)^{\theta/2+1} \mathrm{F}\left(1,1+\theta/2;2+\theta/2;e^{i2\pi\alpha}\frac{1-\sqrt{\xi}}{1+\sqrt{\xi}}\right).$$

$$\int_0^a \frac{\cos\pi\varphi(2-\theta)\cos\pi\alpha\theta - \cos\pi\alpha(2-\theta)\cos\pi\varphi\theta}{\cos 2\pi\varphi - \cos 2\pi\alpha}d\varphi = \frac{a\sqrt{k_2(k_1-k_2)}}{Q}$$

$$\pi\theta = 2\arcsin\sqrt{k_2/k_1} = 2\arcsin\sqrt{k}$$

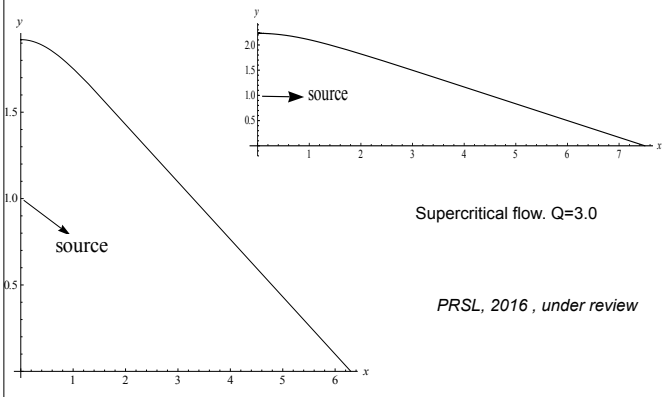
Phreatic surface, curve 1. Subcritical flow with $k=k_2/k_1=0.1$
Three characteristic flow zones :
- Close to the source the Riesenkampf flow from an isolated source
- Almost 1-D and vertical seepage.
- Close to the substratum, the "impinging seepage jet" solution of Kacimov and Obnosov(2015)



$(x^*,y^*,L^*,b^*) = (x,y,L,b)/a,\ Q^* = Q/(k_1 a)$

Water Resour. Res., 2015

Saturated bulbs for subcritical flow. Q=0.5

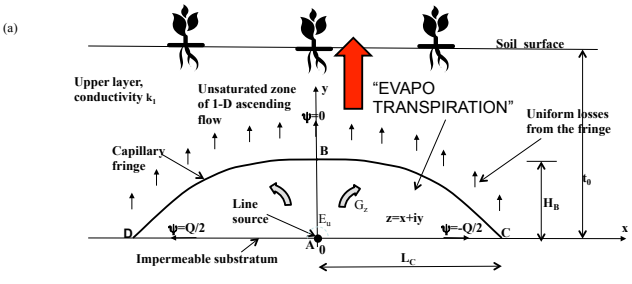


Supercritical flow. Q=3.0

PRSL, 2016 , under review

Critical flow. Q_{cr}=2.52

Riesenkampf's (1938) line source over impermeable substratum



$$\begin{cases} \psi = 0 \text{ along AB}, \\ \psi = -Q/2 \text{ along AC}, \\ \varphi = -k_1(y - H_B), \psi = -ex \text{ along BC} \end{cases}$$

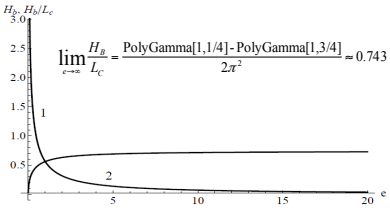
Final solution:

$$z(\zeta)=\frac{Q}{\pi\sqrt{k_1 e}}\int_o^{\zeta}\frac{\sinh(\mu\ u)}{\sinh(u)}du,\qquad \tan\frac{\mu\pi}{2}=\sqrt{\frac{k_1}{e}}$$

$$w(\zeta)=\frac{iQ}{\pi}\int_{i\pi/2}^{\zeta}\frac{\cosh(\mu\ u)}{\sinh(u)}du,$$

$$H_B=\frac{Q}{\pi\sqrt{e}}\int_o^{\pi/2}\frac{\sin(\mu\ u)}{\sin(u)}du$$

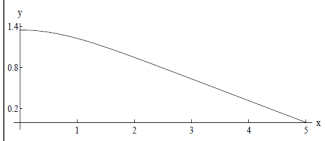
$$L_C=\frac{Q}{2e},$$



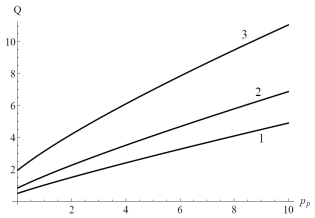
$$\lim_{e\to\infty}\frac{H_B}{L_C}=\frac{\text{PolyGamma}[1,1/4]-\text{PolyGamma}[1,3/4]}{2\pi^2}\approx 0.743$$

$H_B(e)$ and aspect ratio $H_B/L_C(e)$ (curves 1-2) for $Q=1$ as functions of evaporation rate.

$Q^*=Q/(k_1 h_c),(z^*,H_B^*,L_C^*,)=(z,H_B,L_C)/h_c, c^*=c/k_1$



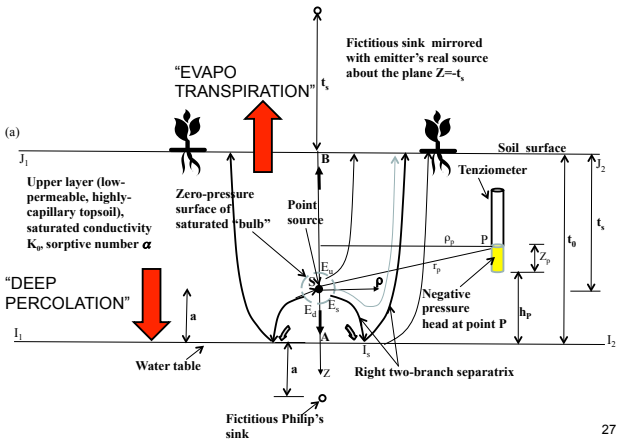
Capillary fringe for $Q=1$, $e=0.1$



Q as a function of pipe pressure head p_p for $e=0.1$ and R=0.001,0.01 and 0.1

$$p_p=\frac{Q}{\pi}\log\left[\frac{Q\mu}{\pi R\sqrt{e}}\right]+H_B-1-R$$

Philip's (1989) point source over water table



$$k_{un}=k\exp[\alpha\ p]$$

$$\theta=\int_{-\infty}^{p}k_{un}(p)d\ p=\frac{k_{un}[p(\rho,Z)]}{\alpha}$$

$$\Delta\theta=\alpha\frac{\partial\theta}{\partial Z},$$

$$V_\rho=-\frac{\partial\theta}{\partial\rho},V_Z=\alpha\theta-\frac{\partial\theta}{\partial Z}$$

$$\theta_{Ph}=\exp[2(z-a)]+\frac{Q\exp z}{8\pi}\left[\frac{\exp(-r)}{r}-\frac{\exp(-r_1)}{r_1}\right],$$

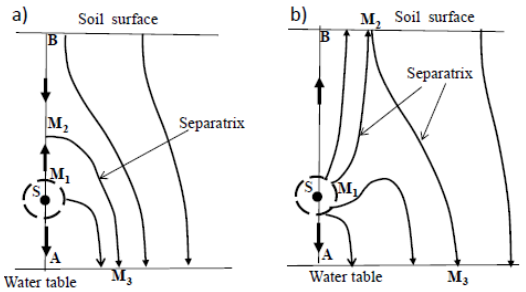
$$r=\sqrt{\rho^2+z^2},\quad r_1=\sqrt{\rho^2+(z-2a)^2}$$

$$\theta_{1D}=\frac{\theta_0\left[\exp[2(a+t_s)]-\exp[2(Z+t_s)]\right]+\exp[2(Z+t_s)]-1}{\exp[2(a+t_s)]-1},$$

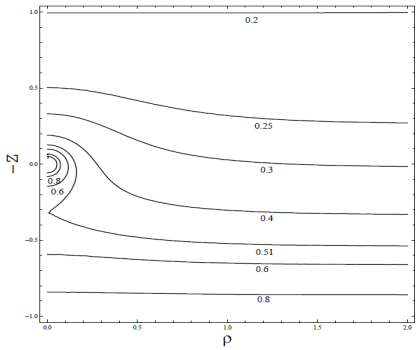
$$V_{Z1D}=2\frac{\theta_0\exp[2(a+t_s)]-1}{\exp[2(a+t_s)]-1}$$

Final solution:

$$\theta\approx\theta_{1D}+\frac{Q\exp z}{8\pi}\left[\frac{\exp(-r)}{r}-\frac{\exp(-r_1)}{r_1}-\frac{\exp(-r_2)}{r_2}\right],\ r_2=\sqrt{\rho^2+(z+2t_s)^2}$$

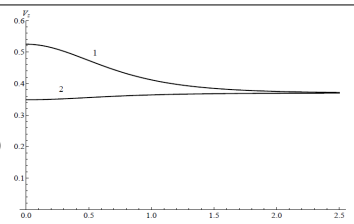


Flow topology for bulk infiltration from the soil surface to the water table: a weak source (a) and strong source (b).

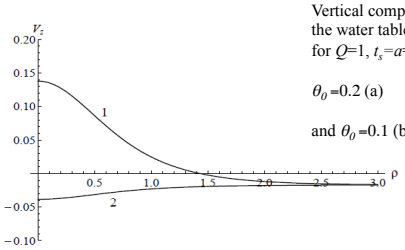


Contour lines of Kirchhoff's potential θ=1.0, 0.8, 0.6, 0.51, 0.4, 0.3, 0.25, 0.1 plotted for for θ_0=0.2, Q=1, t_s=a=1

a)



b)



Vertical component of Darcian velocity along the water table (curve 1) and topsoil (curve 2) for Q=1, t_s=a=1 and soil surface potentials:

θ_0=0.2 (a)

and θ_0=0.1 (b).

6. Conclusions

Smartly designed soil (silt blocks+proppant-filled cracks), combined with smart Irrigation, result in a smart plant growing with optimal control of topology of water fluxes:

- Infiltration
- Evapotranspiration
- Deep percolation
- Irrigation
- Translocation of fine particulates driven by vertical cyclostationary seepage gradients

We addressed:

a) **Simple** agroengineering arsenal leading to better WUE in arid climates
b) More tortuous flow path and longer residence time in the vadose zone
c) Maintenance/resilience of unique edaphic-factor controlled desert ecosystems
d) Novel and aesthetically beautiful mathematical 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

"We no longer collect, we squander the capital of our ancestors, even in the way in which we seek knowledge."

F.Nietzsche, Will to Power

"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