Water, heat, and vapor flow in a deep vadose zone under arid and hyper-arid conditions: a numerical study

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Rationale

Groundwater recharge in arid regions is driven by irregular rainfall that infiltrates into deep vadose zones in which water moves as a liquid as well as a vapor. The processes below the root zone are underresearched.

Approach

- Simulation of flow of liquid water, heat, and vapor
- 100 m deep profile of an unvegetated sandy loam
- Geothermal gradient: 3.5℃ / 100 m
- Two parameterizations of the retention curve, tailored for dry conditions
- Burn-in period, then 120-year period with two synthetic rainfall records

Objectives

- Examine the effect of the soil hydraulic parameterization
- Determine which features of the rainfall record generate groundwater recharge
- Quantify the effect of vapor flow in a deep vadose zone

Numerical model

Hydrus_1D (Šimůnek et al., 2016): solver for the coupled Richards' and heat flow equations. Diffusive vapor flow with instantaneous equilibrium between the matric potential and the vapor pressure.

The daily temperature model

Hydrus_1D needs the daily minimum (T_{MIN}) and maximum temperature (T_{MAX}) on input.

- Annual sinusoidal trend for the daily mean
- Normally distributed white noise superimposed
- T_{MAX} - T_{MIN} lognormally distributed, centered around the mean

$$T_{\substack{MIN\\MAX}} = \overline{T} + A\left\{\sin\left[\frac{2\pi(\varphi+t)}{365.25}\right]\right\} + \sigma_m N_1(0,1) \mp e^{\mu_f + \sigma_f N_2(0,1)}$$

- Parameters fitted to the temperature record of Riyadh (Saudi Arabia)

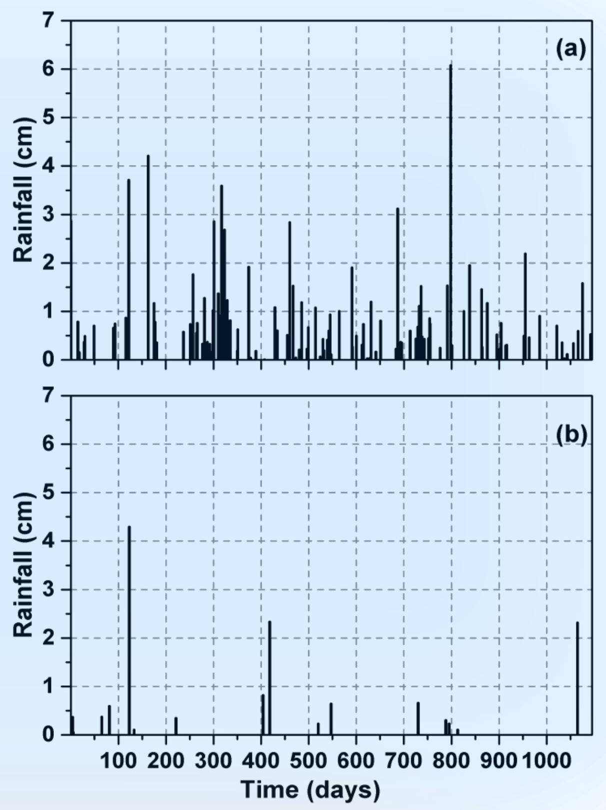
The rainfall records

Truncated modified Bartlett-Lewis model with gamma-distributed rainfall rates (Pham et al. 2013)

Dry season: Dec - Sep.
Wet season: Oct - Nov.

Arid rainfall: 31 cm yr^{-1} (a)
Hyper-arid rainfall: 8 cm yr^{-1} (b)

Graphs show 3-year samples



The soil hydraulic parameterizations

- Non-zero air-entry value to keep hydraulic conductivity near saturation realistic (Ippisch et al., 2006)
- The dry end is logarithmic

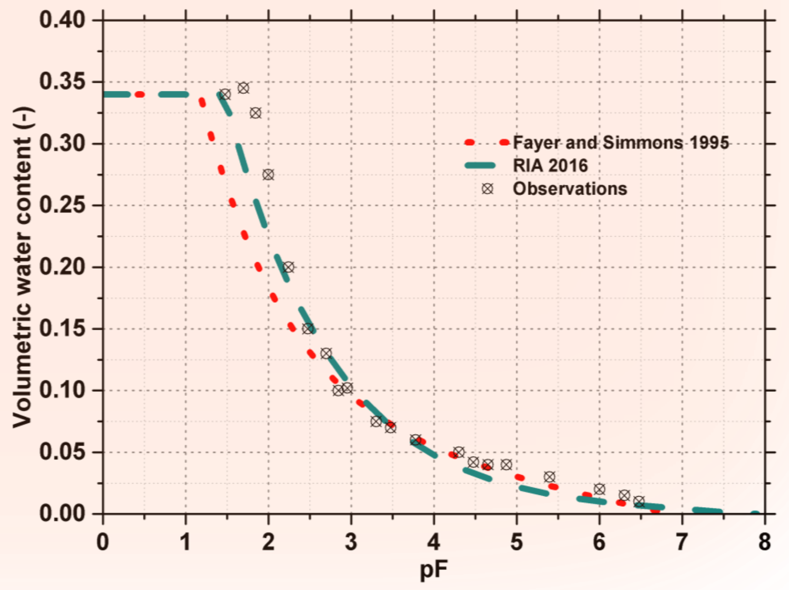
Fayer and Simmons (1995) (FSB):

$$\theta(h) = \begin{cases} 0, & h \le h_d \\ \theta_a\left(1-\frac{\ln|h|}{\ln|h_d|}\right) + \left[\theta_s - \theta_a\left(1-\frac{\ln|h|}{\ln|h_d|}\right)\right]\left(\frac{h_{ae}}{h}\right)^{\lambda}, & h_d < h < h_{ae} \\ \theta_s, & h \ge h_{ae} \end{cases}$$

Developed by us, based on Ippisch et al. (2006) (RIA):

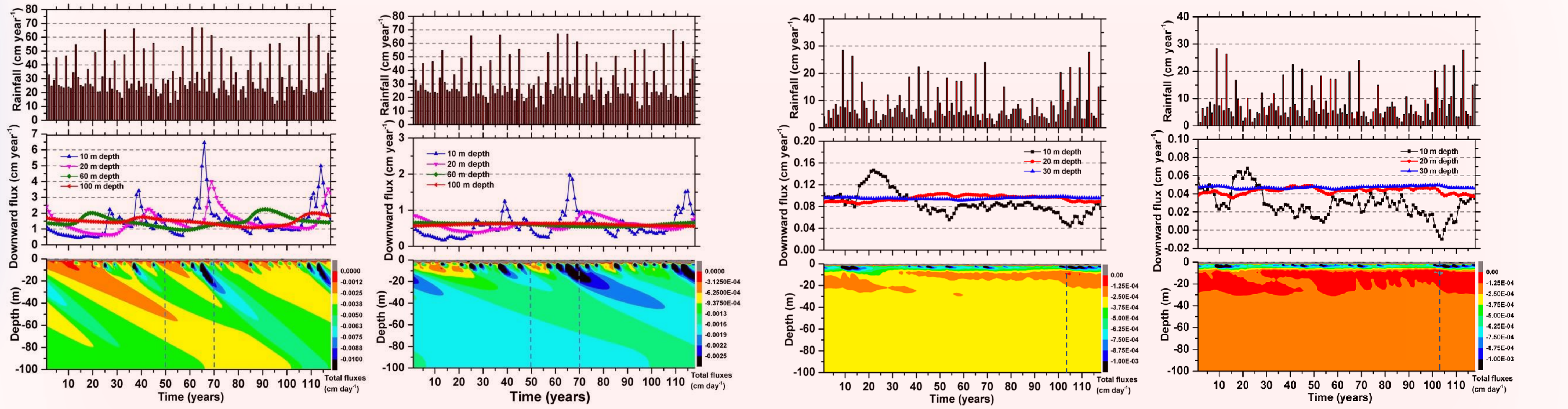
$$\theta(h) = \begin{cases} 0, & h \le h_d \\ \theta_s \beta \ln\left(h_d / h\right), & h_d < h \le h_j \\ \theta_s\left(1+|\alpha h_{ae}|^n\right)^{1-1/n}\left(1+|\alpha h|^n\right)^{1/n - 1}, & h_j < h \le h_{ae} \\ \theta_s, & h > h_{ae} \end{cases}$$

Both functions were combined with Mualem's (1976) conductivity function.



Infiltration is dominated by clusters of wet years and takes decades to move down

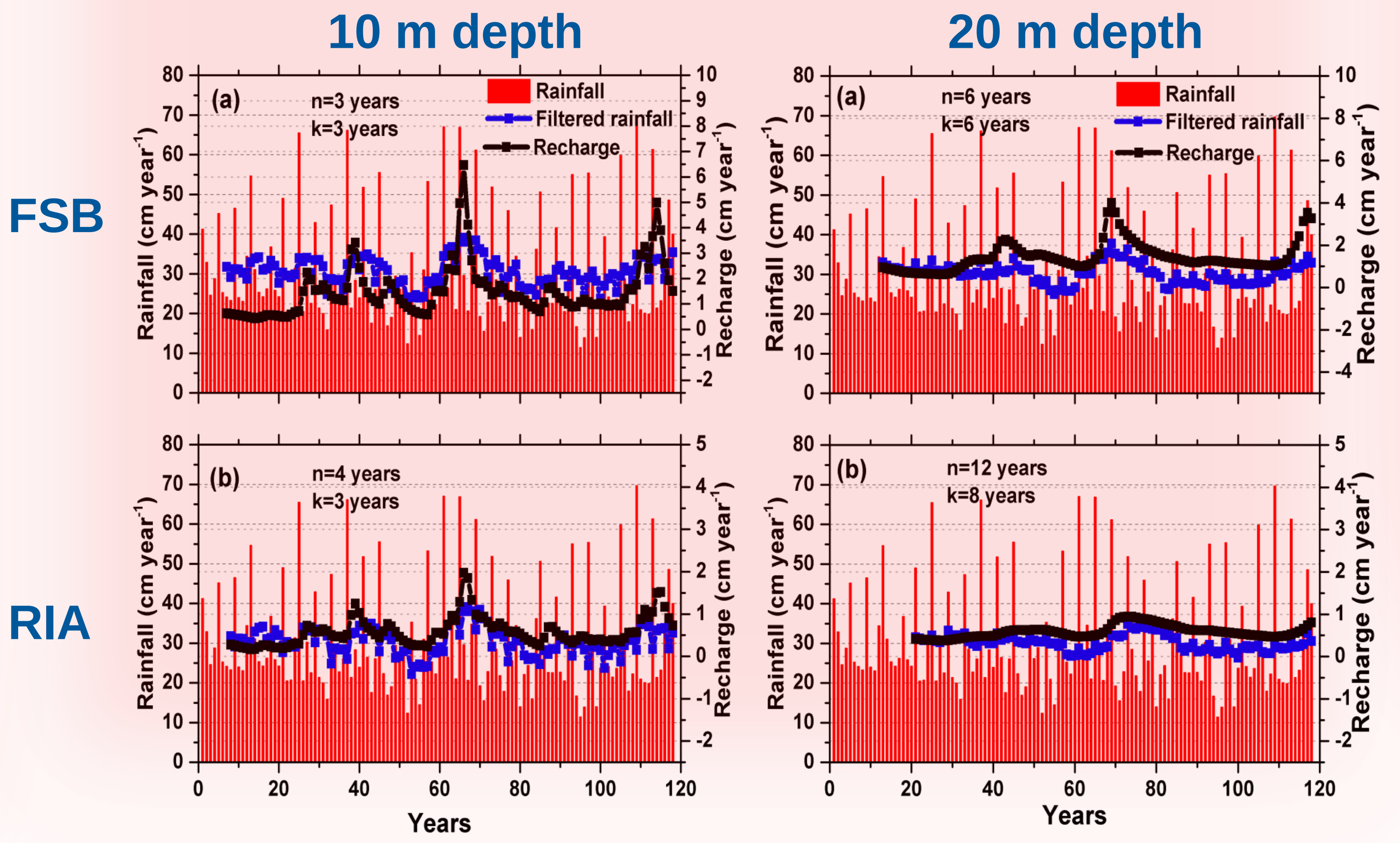
Arid, FSB | Arid, RIA | Hyper-arid, FSB | Hyper-arid, RIA



RIA damps and slows the signal more than FSB. In arid soils, infiltration variations penetrate to 60 (RIA) or 100 m (FSB). In hyper-arid soils, there is no temporal variation below 30 m. FSB generates considerably more groundwater recharge than RIA in both rainfall regimes.

The vadose zone filters the rainfall signal

The arid rainfall signal is delayed by n years and averaged over 2k + 1 years. FSB gives a more spiked signal than RIA, and is 6 years faster at 20 m depth. The hyper-arid signal damps out rapidly (not shown).



Vapor flow below 8 m is (nearly) zero

- Evaporation from the top soil determines how much water is available for groundwater recharge
- Vapor flow affects recharge by a few percent only
- Evaporative loss is determined by the parameterization of the retention curve

Total groundwater recharge in cm (% of rainfall)				
	Arid		Hyper-arid	
	FSB	RIA	FSB	RIA
Vapor flow	173.9 (4.8%)	70.7 (1.9%)	15.3 (1.6%)	9.3 (1.0%)
No vapor flow	166.3	66.7	14.9	9.0

Fayer & Simmons, 1995. Water Resour. Res. 31:1233-1238.
Ippisch, Vogel & Bastian, 2006. Adv. Water Resour. 29:1780-1789.
Mualem, 1976. Water Resour. Res. 12:513-522.
Pham, Vanhaute, Vanderberghe, De Baets, & Verhoest, 2013. Hydrol. Earth Syst. Sci. 17:5167-5183.
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