Development and testing of a simplified mechanistic algorithm to calculate the influence of a shallow water table on flow dynamics through vegetative filter strips

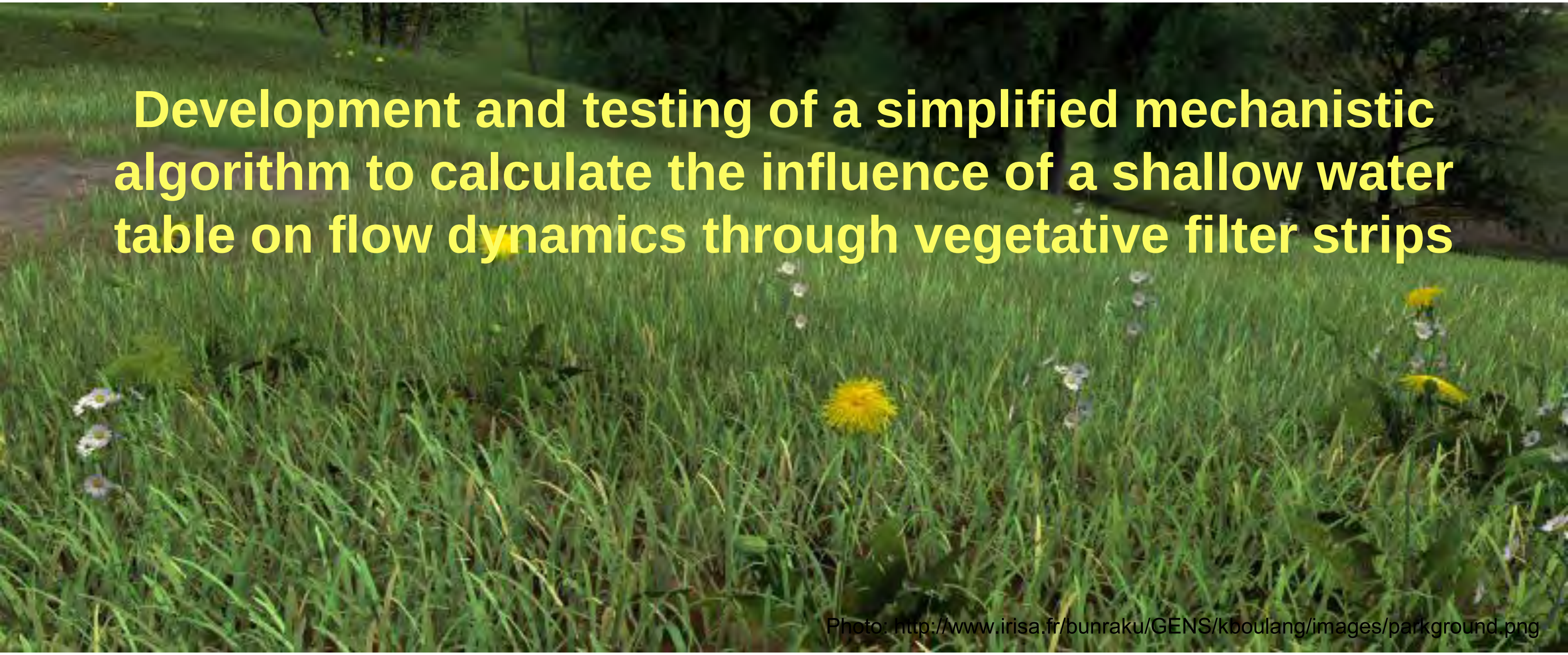

Photo: http://www.irisa.fr/bunraku/GENS/kboulang/images/parkground.png

oz-Carpena[1] , Claire Lauvernet[2] , Nadia Carluer[3]

[1] University of Florida (USA); [2] CEMAGREF-Lyon (France)

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XIV

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Outline

1. Motivation and objectives
2. Conceptual and numerical basis
3. Numerical and experimental validation
4. Applications
5. Effect of water table on VFS efficiency
6. Conclusions

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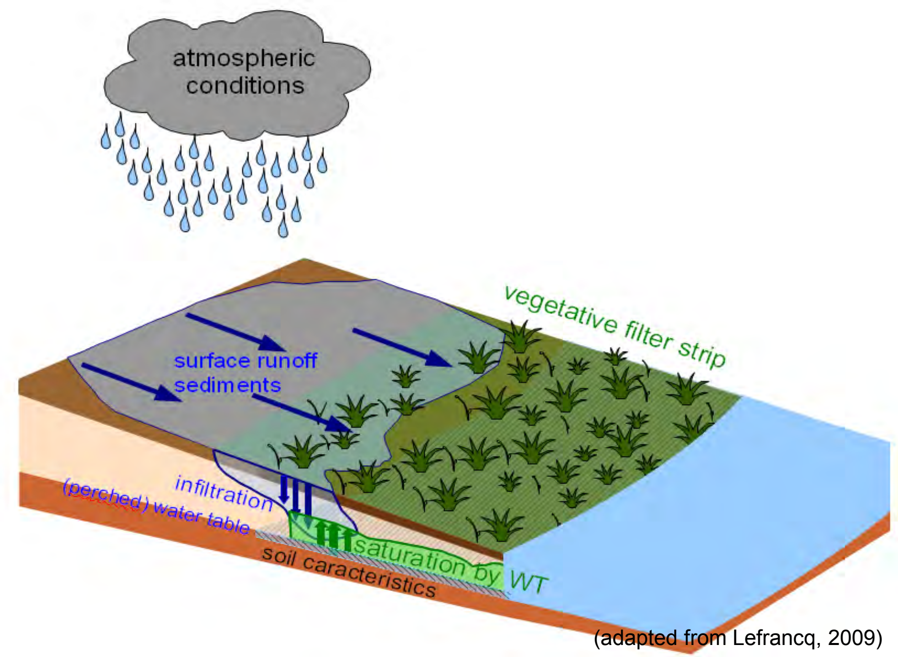
Influence of shallow water table on infiltration and runoff transport?



(adapted from Lefrancq, 2009)

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Soil infiltration with shallow water table

- Salvucci and Enthekabi (1995) proposed an approximate, time-implicit integral solution to the ponded infiltration case for soils bounded by a water table (i.e. under a hydrostatic equilibrium initial condition and free flux bottom boundary condition).
- We further developed the solution (Muñoz-Carpena, Lauvernet and Carluer, 2011a,b) to make it numerically explicit in time to account for unsteady rainfall conditions.
- The new infiltration component was validated against a numerical solution (mass conservative mixed formulation finite differences, Celia et al., 1990) of Richards' equation (CHEMFLO-2000)
- The new algorithm was used to study the effect of varying shallow water table depth (0-4 m) and rainfall intensity (0.1-20 cm/h) on 5 distinct soils.
- Coupling it with overland flow and transport equations (VFSMOD).

Salvucci GD, Entekhabi D. Ponded infiltration into soils bounded by a water table. Water Resour. Res. 1995;31:2751-2759.

Muñoz-Carpena, R., C. Lauvernet and N. Carluer. Simplified mechanistic algorithm for unsteady rainfall infiltration and water content distribution in soils with a shallow water table. Submitted to *Advances in Water Resources* (May 2011a, manuscript no. AWR-11-152)

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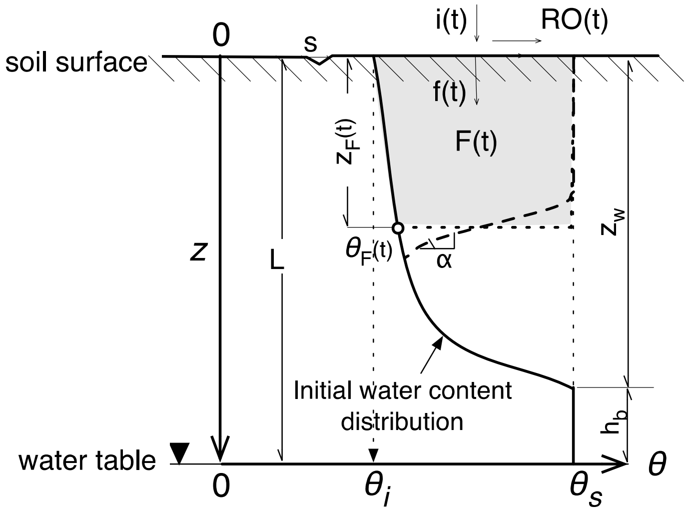


[Neuman, 1976]

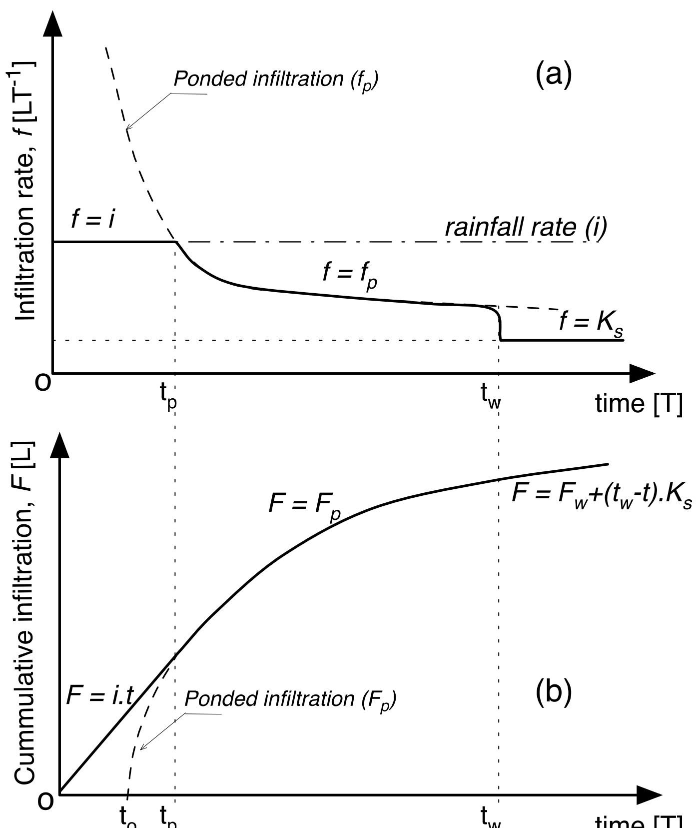
[Bouwer, 1969]

$$G(z,t) = t - t_p + t_0 - \int_0^z \frac{\theta_s - \theta(L-z)}{K_s + \frac{1}{z}\int_0^{L-z} K(h)\,dh}\,dz$$

$$\frac{dG(z,t)}{dz} = -\frac{\theta_s - \theta(L-z)}{K_s + \frac{1}{z}\int_0^{L-z} K(h)\,dh}$$

$$z^{k+1} = z^k - \frac{G(z^k,t)}{\frac{dG(z^k,t)}{dz}} \quad with \quad \left|z^{k+1} - z^k\right| < \varepsilon$$

Conceptual and numerical basis



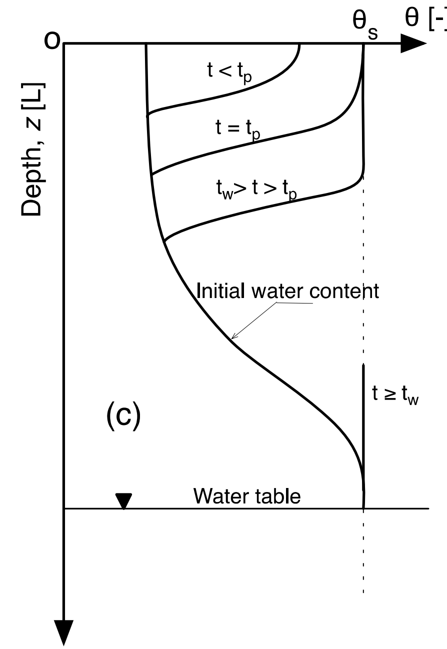


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Table 1. Water Table Depth (L), Brooks and Corey parameters for the different soils and Nash and Sutcliffe coefficient of efficiency (C_{eff}) between the simplified model and Richards' finite differences results (CHEMFLO-2000).

Numerical testing[†]										
Soil	L (m)	θ_r	θ_s	K_s ($m \cdot s^{-1}$)	h_b (m)	λ	η		C_{eff} Richards	
Silty Loam	1.5	0	0.35	3.40×10^{-6}	0.450	1.20	4.67		0.994	
Clay	1.5	0	0.45	3.40×10^{-7}	0.900	0.44	7.54		0.999	
Sandy Loam	1.5	0	0.25	3.40×10^{-5}	0.250	3.30	3.61		0.995	
Vachaud and Thony (1971)	1.01	0	0.35	1.75×10^{-5}	0.181	0.73	4.63		0.976	
Experimental testing[†,††]										
Soil	L (m)	θ_r	θ_s	K_s ($m.s^{-1}$)	α_{vG} (m^{-1})	n	m	α_{Grd} (m^{-1})	n_{Grd}	C_{eff} Richards	C_{eff} data
Vachaud et al., (1974)	0.925	0.107	0.34	2.64×10^{-5}	1.143	2.363	0.652	-	-	0.960	0.913
	0.925	0.107	0.34	2.64×10^{-5}	1.143	2.363	0.652	0.136	2.151	0.939	0.942

[†] h_b, λ, η are the Brooks and Corey parameters, values from Brass (1990); [††] α_{vG}, n, and m are van Genuchten parameters, and α_{Grd} and n_{Grd} are the Gardner parameters (see Appendix for details).

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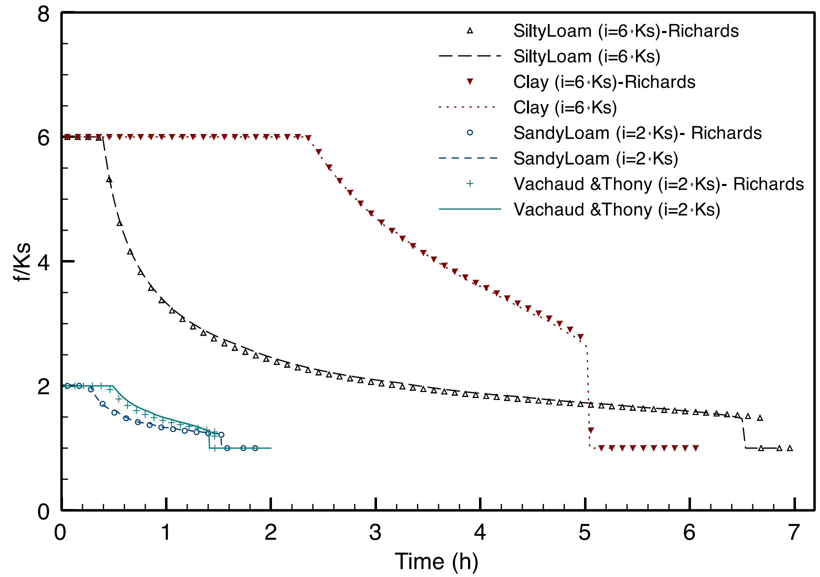

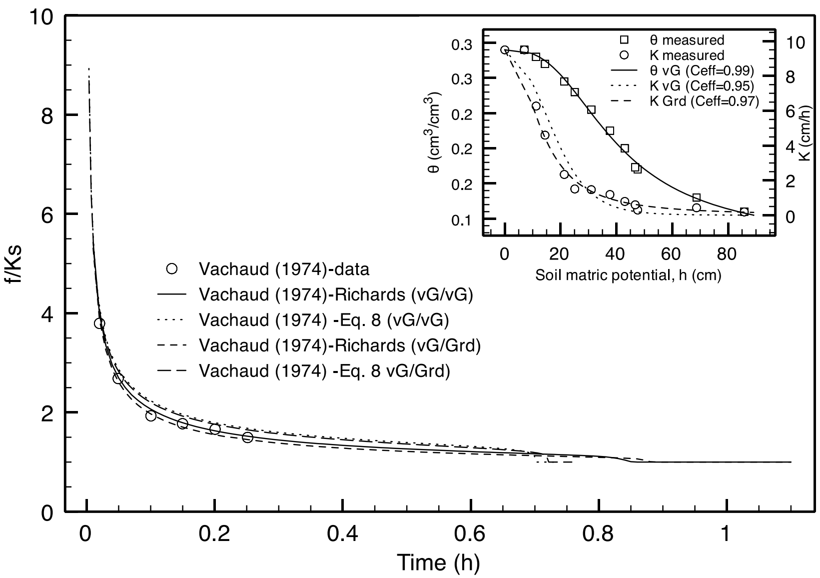

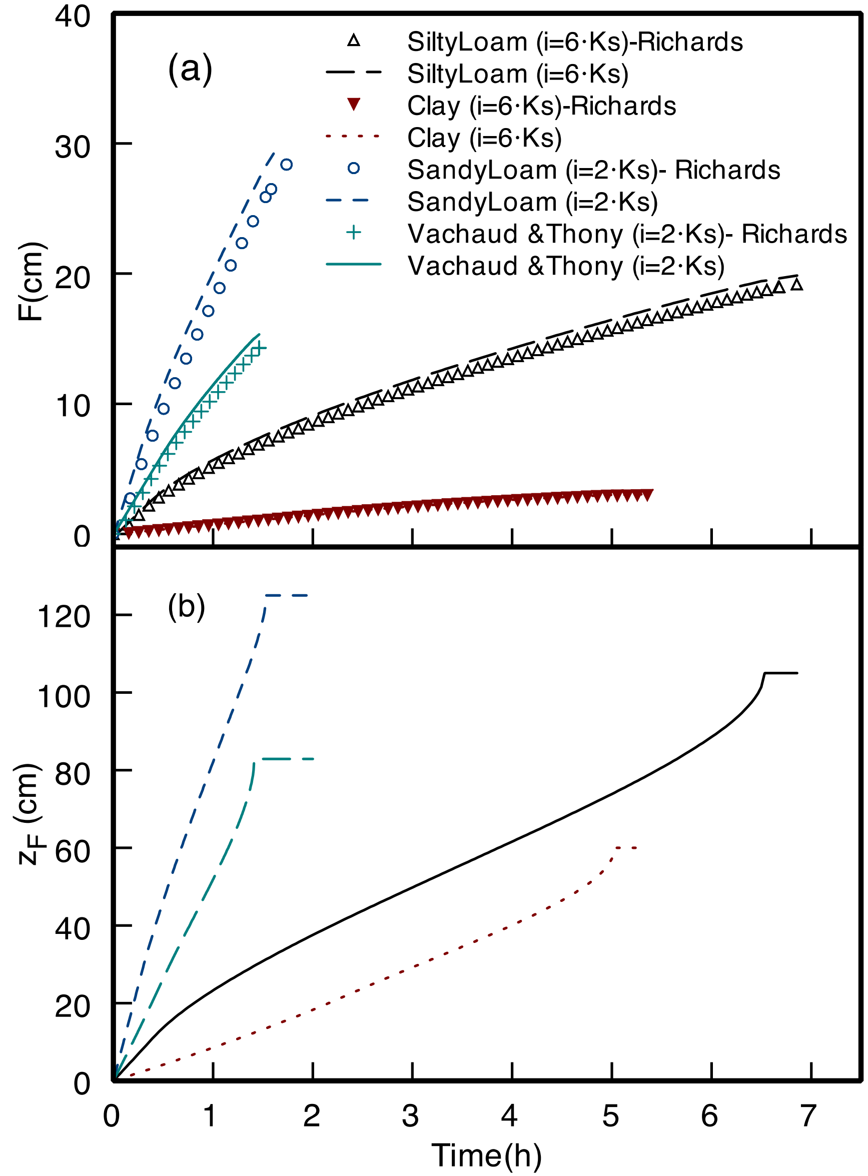

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Validation of infiltration predictions against Richards and experimental data

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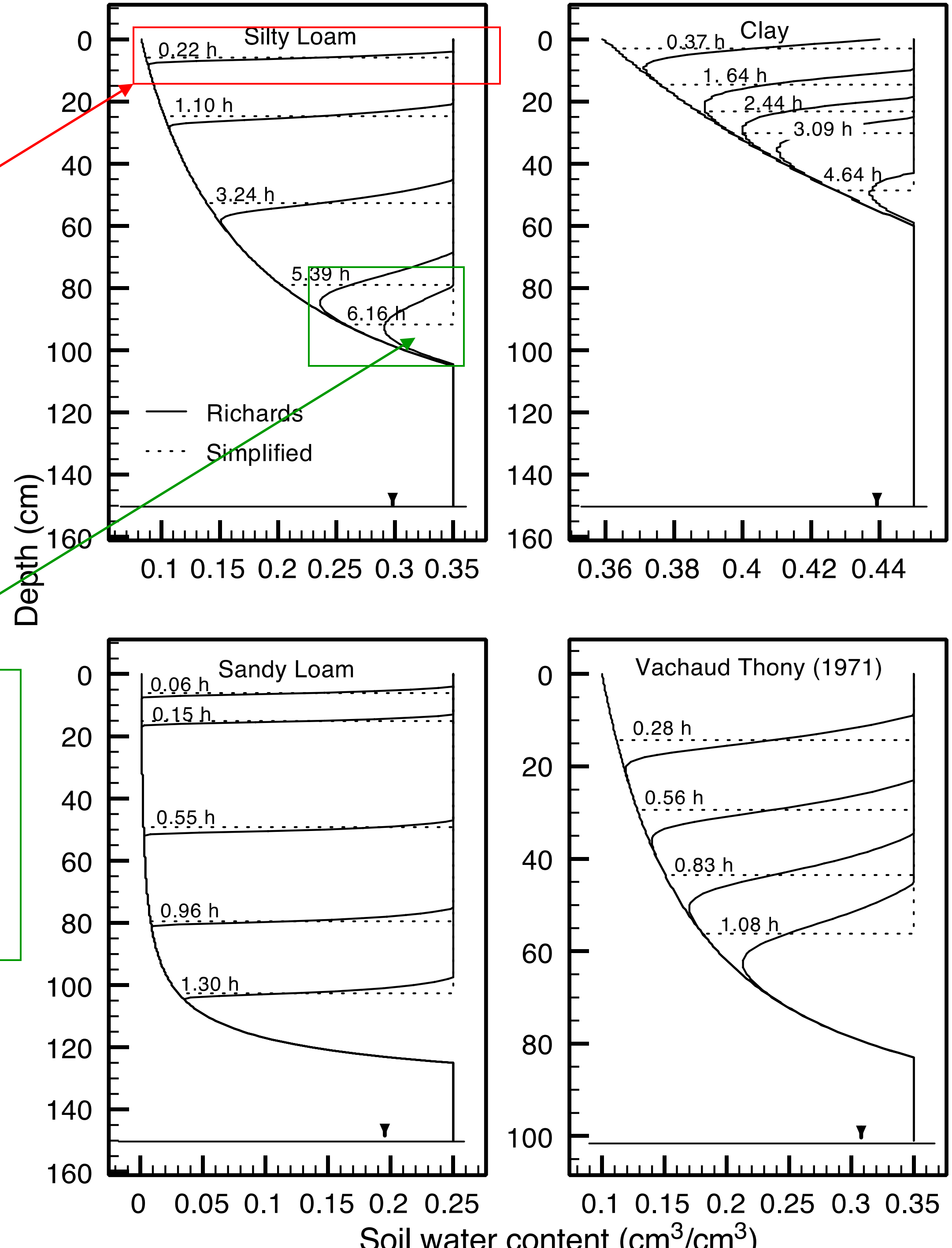
Validation of soil water profile predictions against Richards solution



Close to the surface the front is close to a horizontal shape

deeper → steeper wetting front (especially for fine soils)
But close to the WT, the available pore space is small
→ The mass errors in calculations is limited

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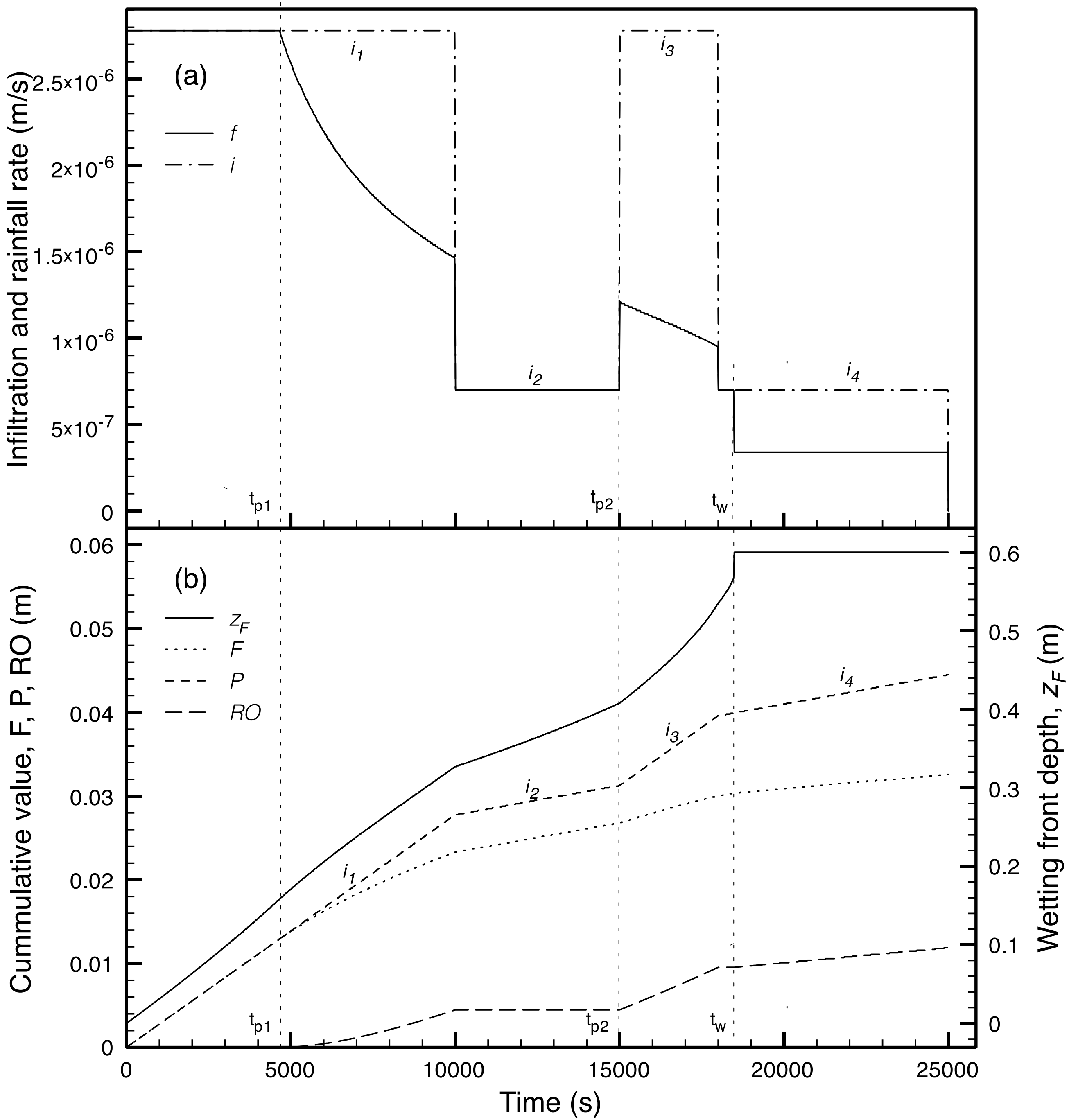
Application to unsteady rain conditions



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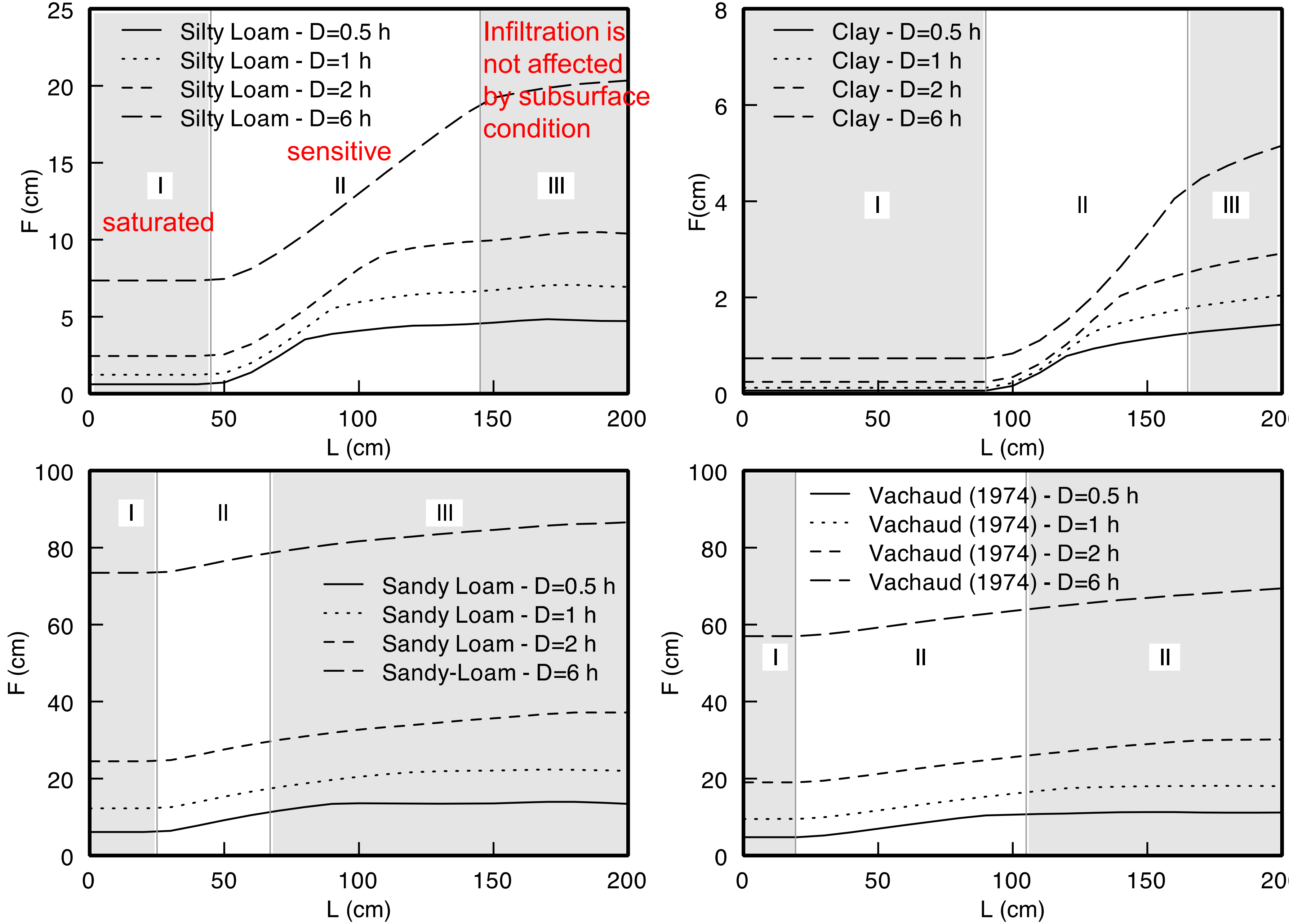

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Effect of water table depth on **ponded** soils for different event durations (6 hrs.)

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Coupling with overland flow module

- Petrov-Galerkin up-winding finite element numerical solution of the overland flow kinematic wave for the 1-D case [*Lighthill and Whitham*, 1955; *Muñoz-Carpena, et al.*, 1993a,b;1999]

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = i_e(t) \quad \textit{(Continuity equation)}$$

$$S_o = S_f \quad \textit{(Momentum equation)}$$

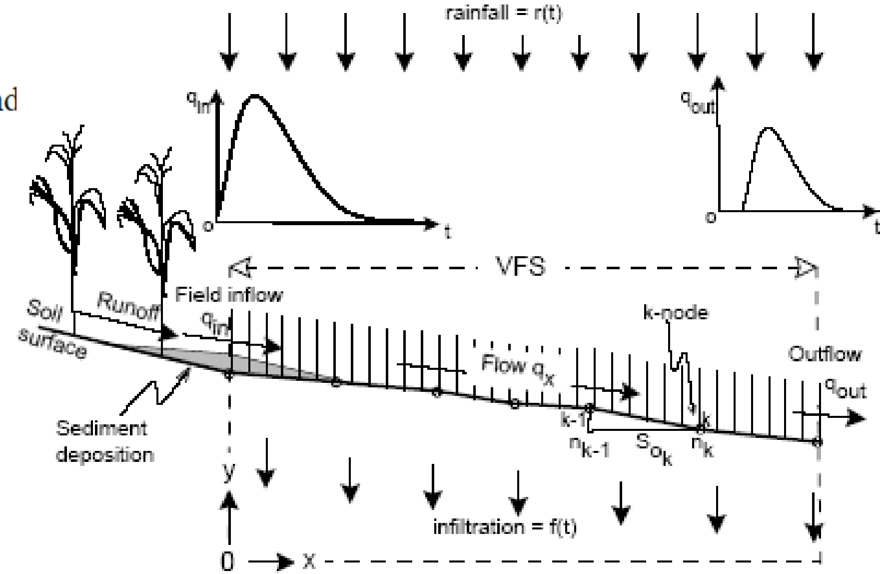
$$q = q(h) = \frac{\sqrt{S_o}}{n} h^{\frac{5}{3}}$$

The initial and boundary cond

$$h = 0;\ 0 \le x \le L;\ t = 0$$

$$h = h_o;\ x = 0;\ t > 0$$

Limits: $Fr = \frac{v}{\sqrt{gh}} < 1.5$ and $k = \frac{L S_o g}{v^2} > 10$



Domain Discretization (Muñoz-Carpena et al., 1999)

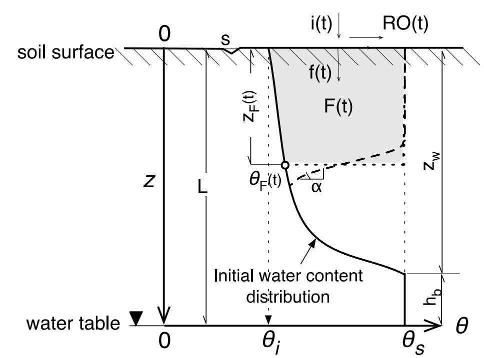
Coupling of new infiltration algorithm with overland flow:

$$F_z = q_s z_F + \int_L^{L-z_F} q(h)\,dh = q_s z_F - \int_0^{z_F} q(L-z)\,dz \qquad f_p = q = K_s + \frac{1}{z}\int_0^{L-z_F} K(h)\,dh$$

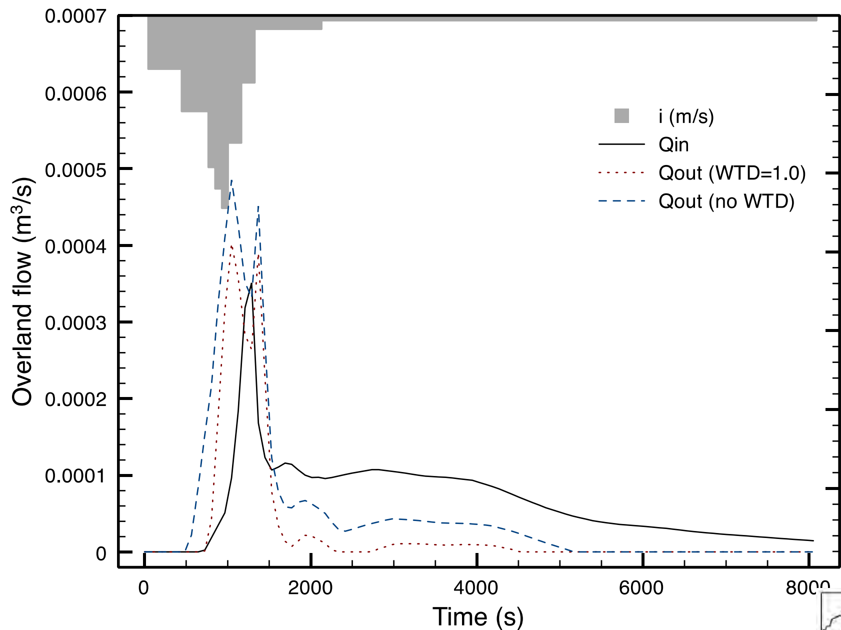
$$G(z,t) = t - t_p + t_0 - \int_0^{z} \frac{q_s - q(L-z)}{K_s + \frac{1}{z}\int_0^{L-z} K(h)\,dh}\,dz$$

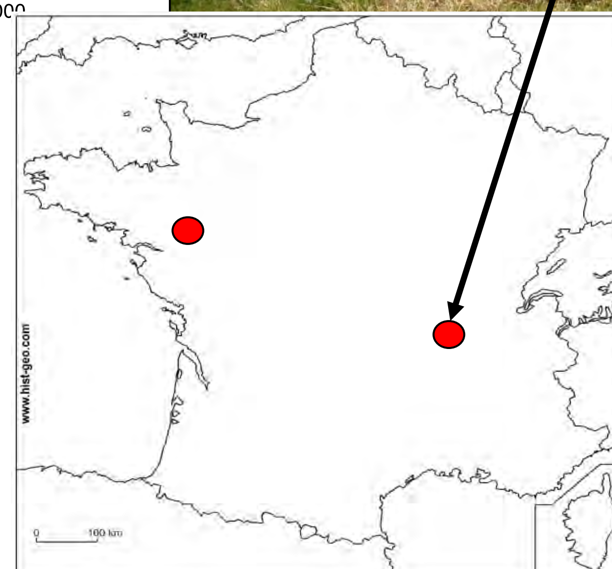
$$\frac{dG(z,t)}{dz} = -\frac{q_s - q(L-z)}{K_s + \frac{1}{z}\int_0^{L-z} K(h)\,dh}$$

$$z^{k+1} = z^k - \frac{G(z^k,t)}{\frac{dG(z^k,t)}{dz}} \quad \textit{with} \quad \left|z^{k+1} - z^k\right| < e$$



Case 1: Morcille-Isoproturon (Beaujolais, FR)





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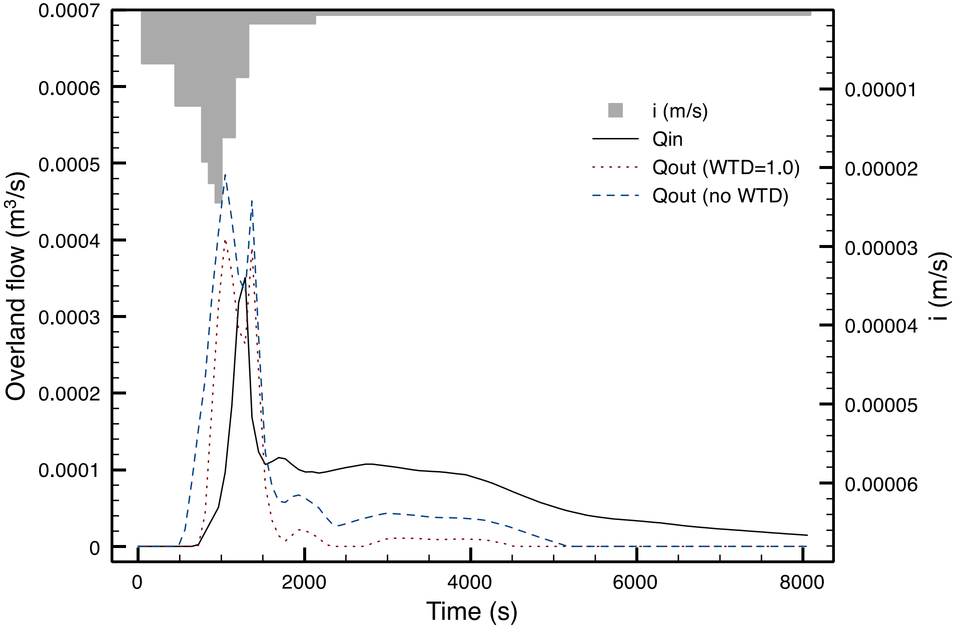
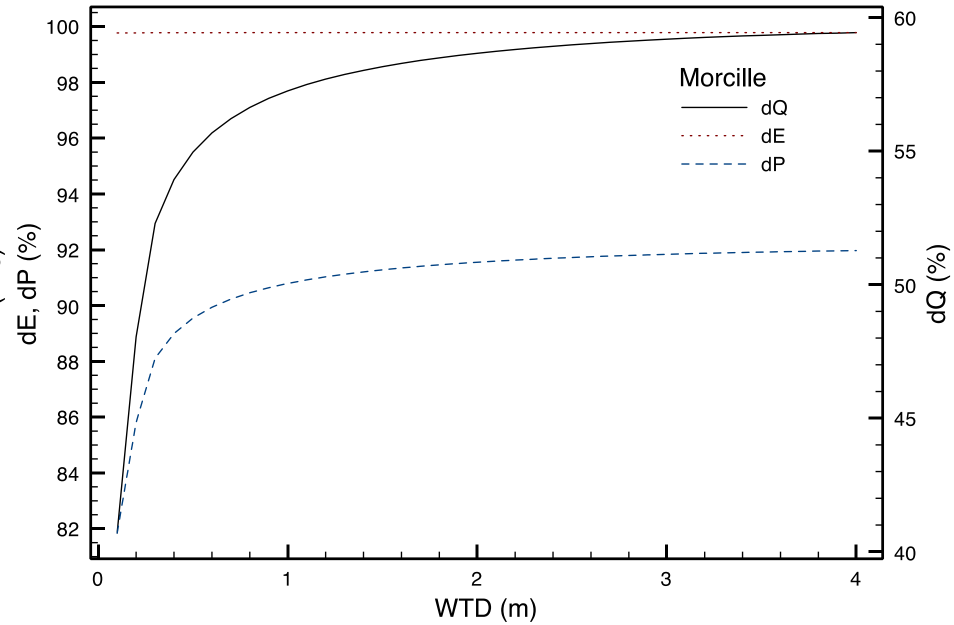
- wineyard
- permeable sandy-clay
- slope = 25%

Case 1: Morcille-Isoproturon (Beaujolais, FR)





- dQ is sensitive to WTD but the response is non-linear (highest sensitivity between 0-1 m of water table depth)
- For a coarse sediment in this area the filter is very efficient in trapping sediment and is not affected by the WTD (already at max).
- dP response to WTD changes follows that of the water for this predominantly dissolved pesticide.

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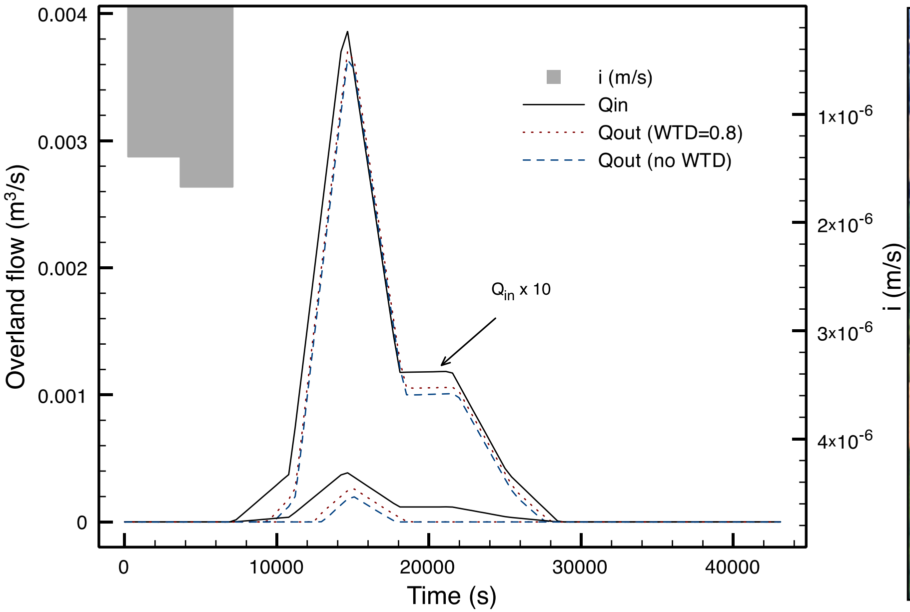
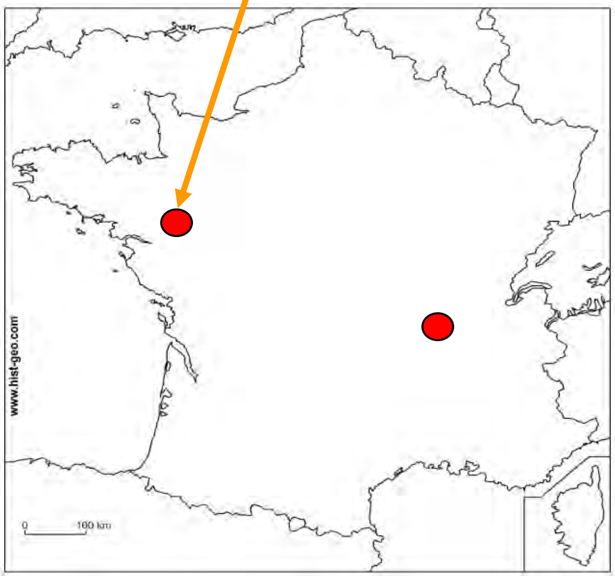
Case 2: Jailliere-Isoproturon (Loire-Atlantique, FR)





- ARVALIS–Institut du Végétal
- wheat and maize crops
- silty clay
- slope = 3%

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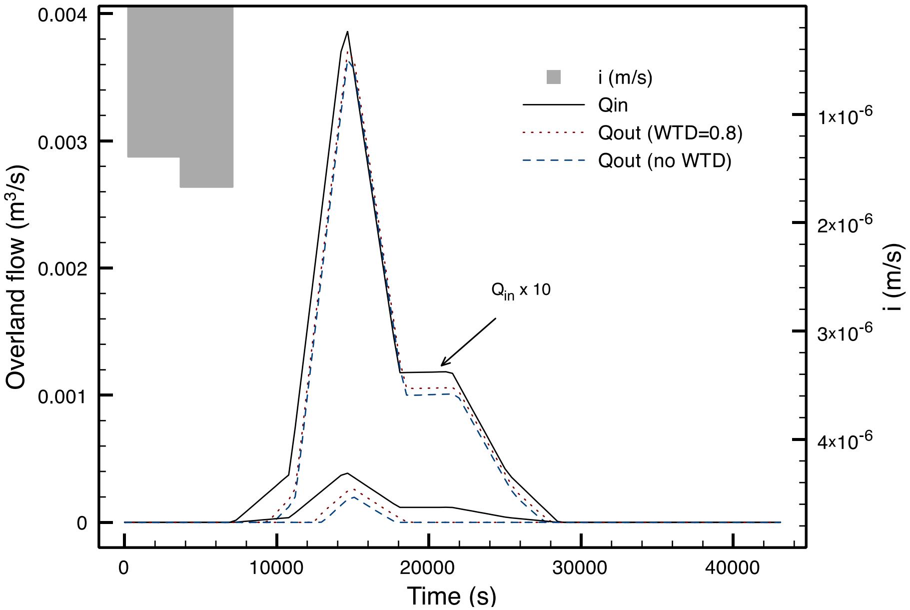
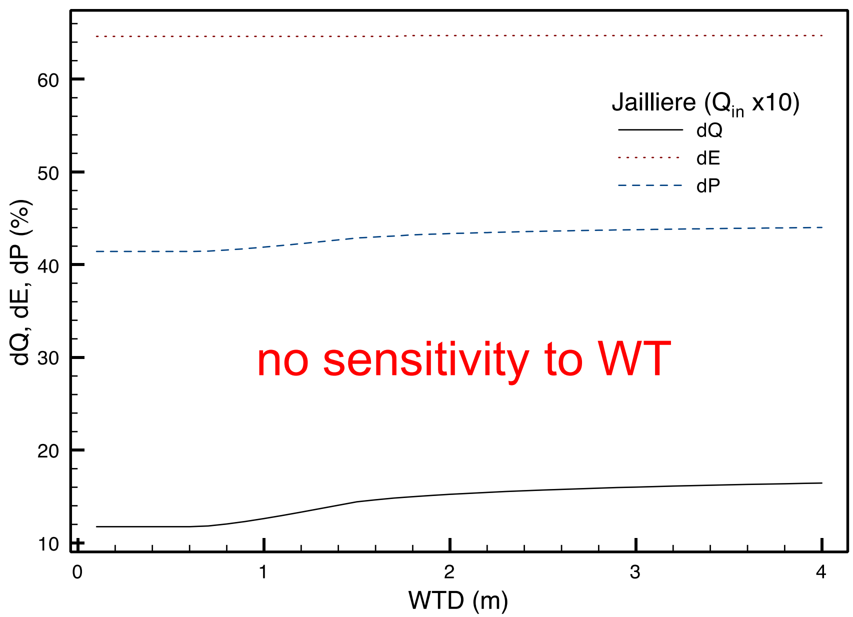
Case 2: Jailliere-Isoproturon (Loire-Atlantique, FR)





- dP response to WTD depends on hydraulic loading (sum of all water entering the filter, $i+Q_{in}$).

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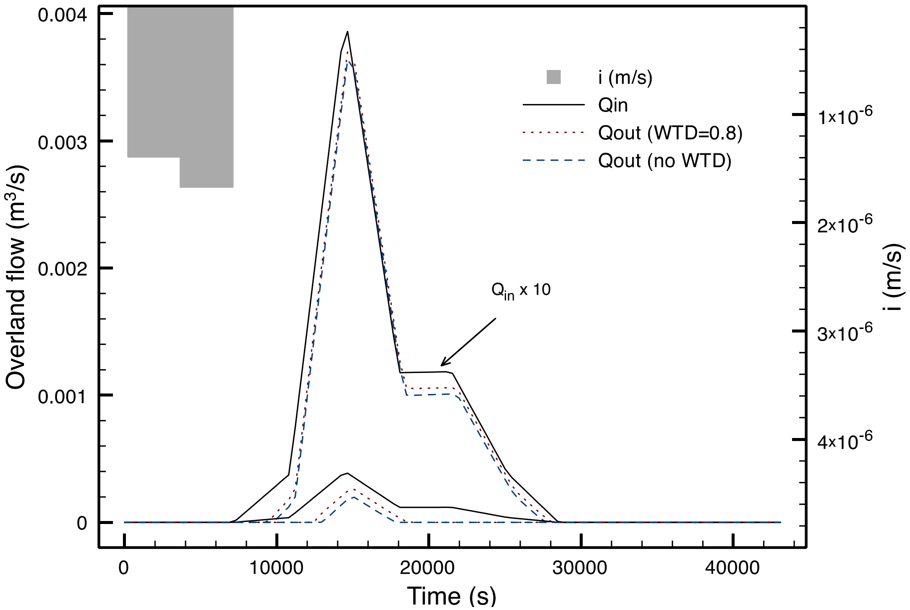
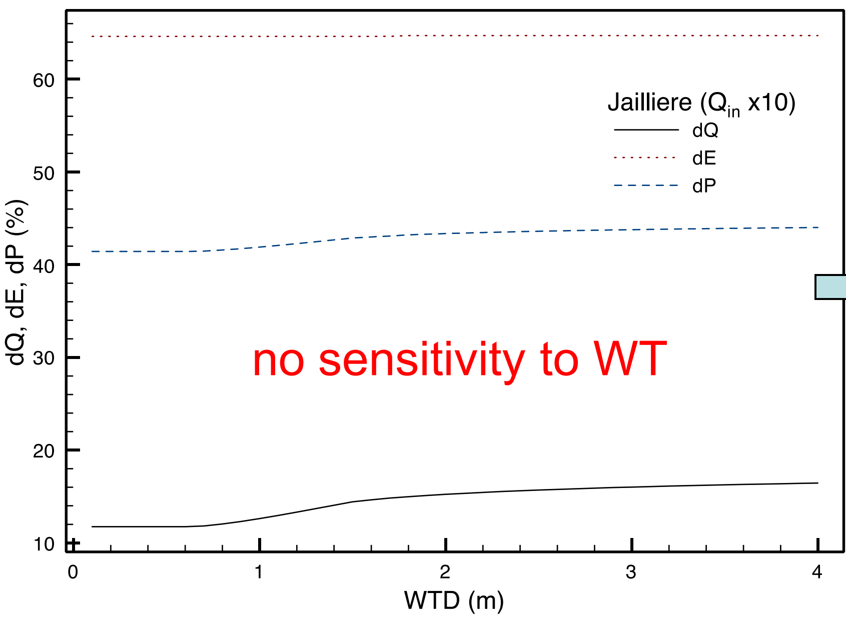
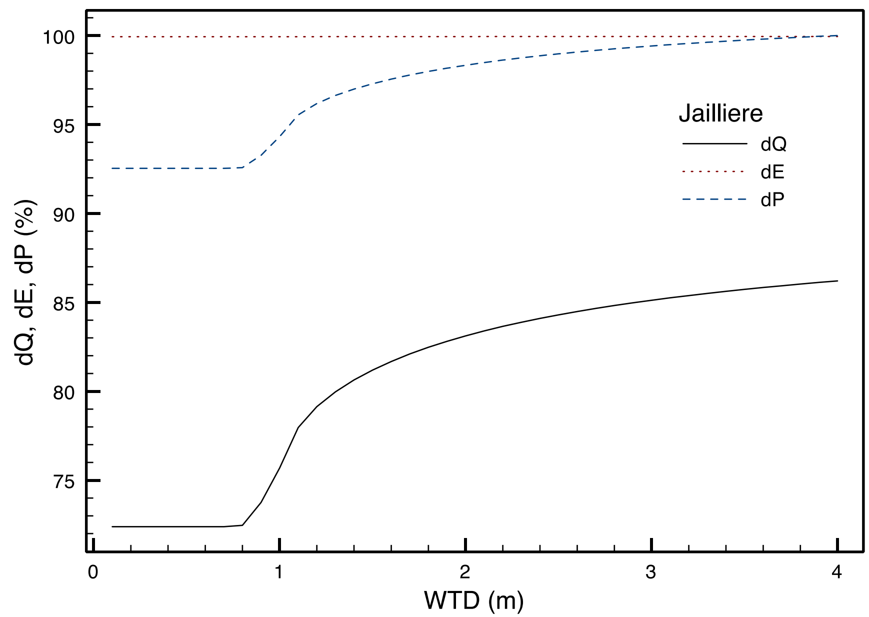
Case 2: Jailliere-Isoproturon (Loire-Atlantique, FR)



- dP response to WTD depends on hydraulic loading (sum of all water entering the filter, $i+Q_{in}$).
- Sediment trapping at high loading is not sensitive because the increase in surface flow caused by WTD is relatively small, while for low loading the reduction is maximum (and also insensitive)





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Conclusions

- Results show that the influence of the shallow water table on the VFS infiltration and runoff is significant for depths shallower than 1-1.5 m, but that this influence becomes negligible when the water table is deeper.
- As expected, the influence of rainfall intensity varies with the duration of the storm, soil characteristics (more important in fine soils) and water table depth.
- Soils that exhibit a marked air entry (bubbling pressure) on their soil water characteristic curve introduce also a distinct behavior for very shallow WTD.
- Sensitivity analysis is needed to complete the model validation (➔ poster!)
- Real data under WT conditions would be very useful…
- Effect on VFS performance is specific to site hydraulic-loading and soil conditions ➔local diagnosis

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Thank you!

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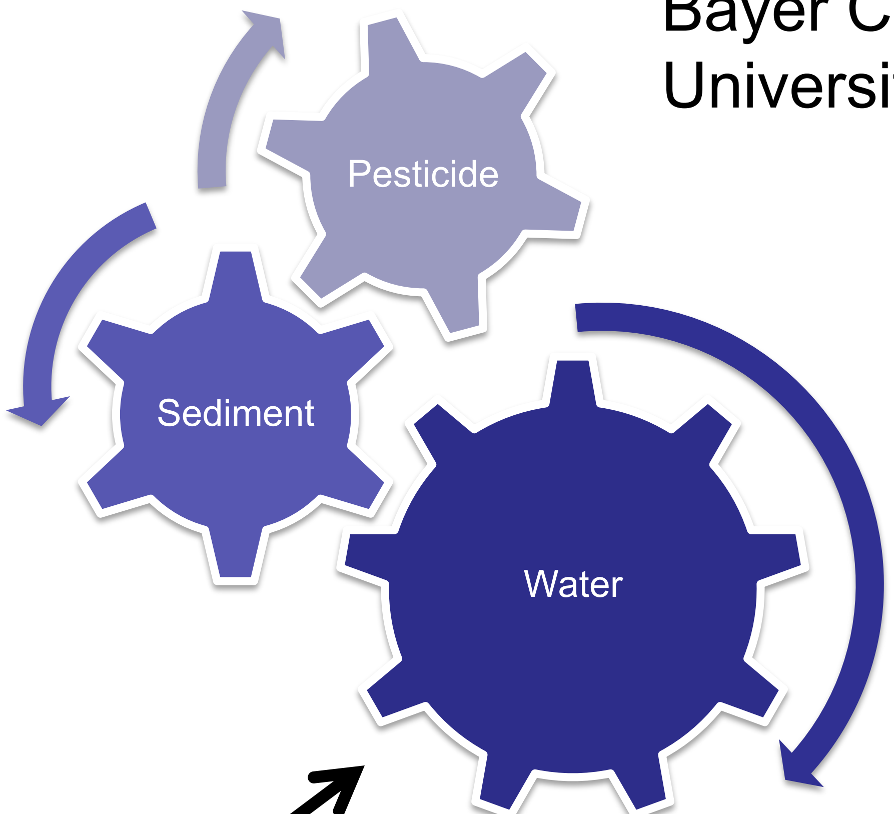
ECPA, Brussels
Bayer CropScience
University of Florida



Water table depth

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