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Institute of Geoecology
Soil Science and Soil Physics

Modelling dynamic non-equilibrium water flow observed in experiments with controlled pressure head or flux boundary conditions

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Introduction

Dynamic non-equilibrium water flow or dynamic effects (DNE) refers to various phenomena which cannot be described by the classical theory. These phenomena are well known since the 1960s and the pioneering work of Topp et al. (1967, SSSAJ). DNE occur mainly as (Hassanisadeh et al. 2002, VZJ; Diamantopoulos and Durner, 2012, VZJ):

1. flow-rate dependence of Soil Hydraulic Properties (SHPs) (Topp et al., 1967, SSSAJ)
2. DNE in MultiStep Outflow (MSO) experiments (Schultze et al., 1999)
3. DNE in MultiStep Flux (MSF) experiments (Weller and Vogel, 2012, VZJ)

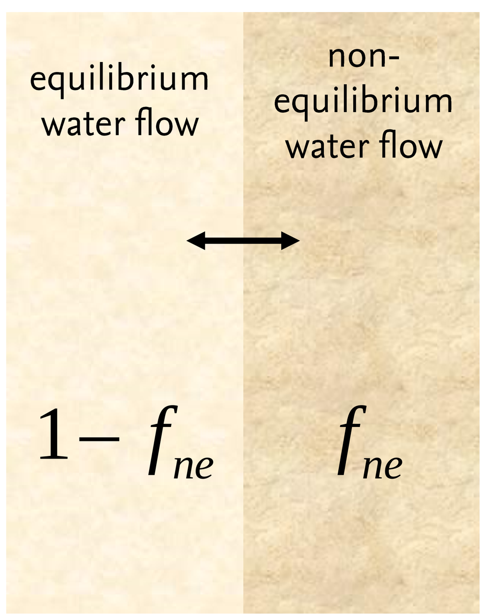
In the first case the SHPs differ under static and transient conditions. In the second case DNE appear as a relaxation in the cumulative outflow while the pressure head in the soil column is at hydrostatic equilibrium. In the third case, MSF experiments, DNE effects appear as a relaxation of the pressure head while the flux density and macroscopic water content distribution appear static.

Scope

Diamantopoulos et al. (2012, WRR) presented a model for describing DNE effects in MSO experiments. In this work we address the question:

Can we simulate the three main observations of DNE experiments by using the same modelling approach?

1. Model description



1. equilibrium domain

Richards equation

$$\frac{\partial \theta_{eq}}{\partial t} = \frac{\partial}{\partial z}\left[K\left(\frac{\partial h_{eq}}{\partial z}\right)-1\right]$$

2. non-equilibrium domain

Ross and Smettem (2000, SSSAJ)

$$\frac{\partial \theta_{ne}}{\partial t} = \frac{\partial}{\partial z}\left[K\left(\frac{\partial h_{ne}}{\partial z}\right)-1\right] \quad \text{where}$$

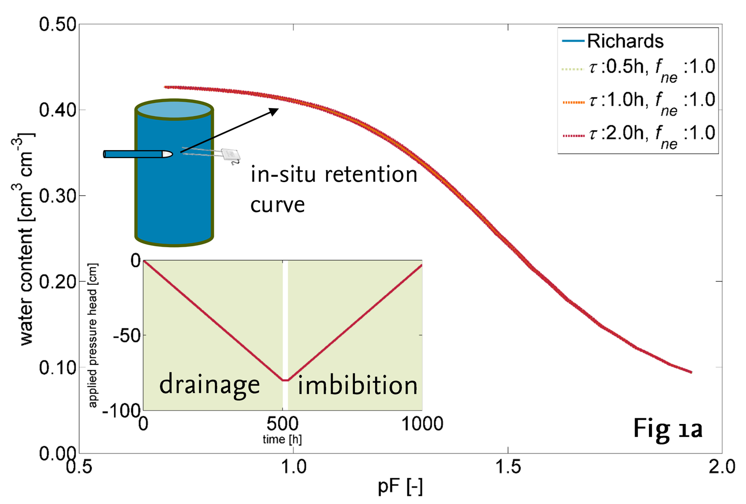
$$\frac{\partial \theta_{ne}}{\partial t} = f(\theta, \theta_{eq}) = \frac{(\theta_{eq}-\theta)}{\tau}$$

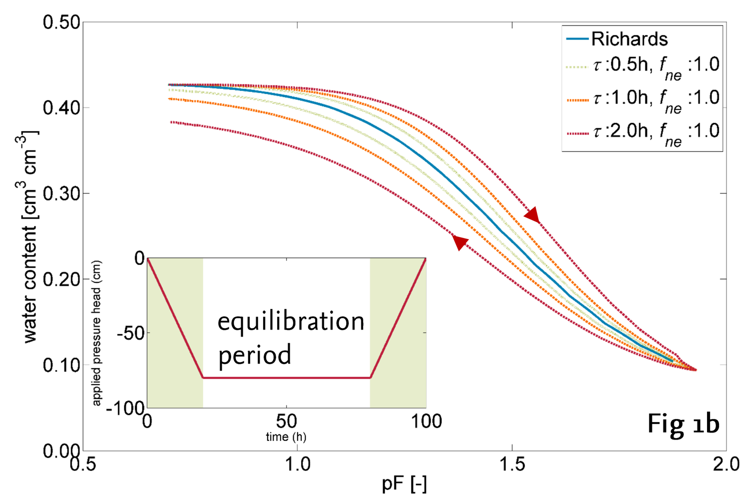
proposed model (Dual-NE, Diamantopoulos et al. (2012, WRR))

$$(1-f_{ne})\frac{\partial \theta_{eq}}{\partial t} + f_{ne}\frac{\partial \theta_{ne}}{\partial t} = \frac{\partial}{\partial z}\left[K\left(\frac{\partial h}{\partial z}\right)-1\right]$$

2. Synthetic data

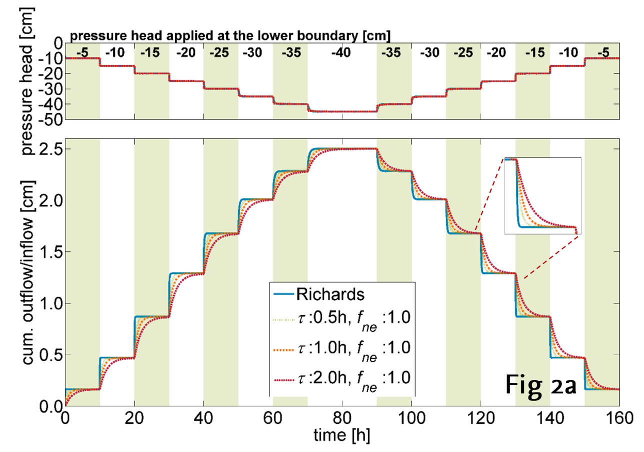
I. Flow rate dependence of SHPs

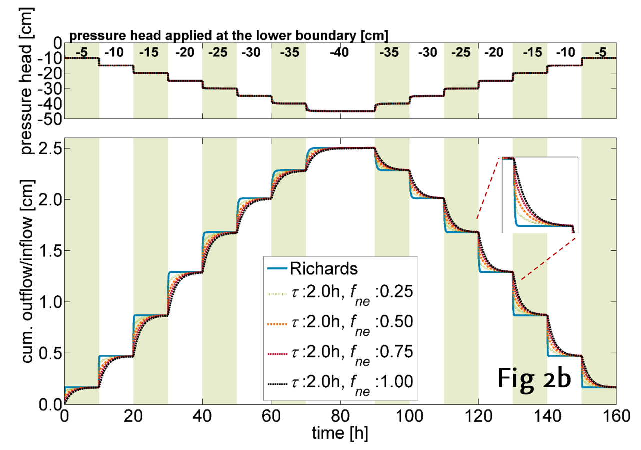




Forward simulations were conducted for two basic drainage-imbibition experiments. In the first case (left) the pressure head at the lower boundary was smoothly changed from 0 to -80 cm in 500 h. After an equilibration time of 24 h it changed from -80 cm to 0 cm again in 500 h. In the second case (right) the pressure head at the lower boundary was smoothly changed from 0 to -80 cm in 20 h, remained there for 60 h, and then it raised again to 0 within 20 h. Forward simulations were conducted with the Richards equation and the Dual-NE for various non-equilibrium parameters. In the first case (slow experiment, **Fig 1a**) the results show that the in-situ measured water retention curves are identical for all models. On the contrary, in the case of the fast drainage-imbibition experiment (fast experiment, **Fig 1b**) an apparent hysteresis is observed for the Dual-NE simulations. In the case of drainage more water is withheld by the soil whereas in the case of imbibition the opposite appears valid. The Richards equation predicts non-hysteretic flow as expected since water content and pressure head are always in equilibrium.

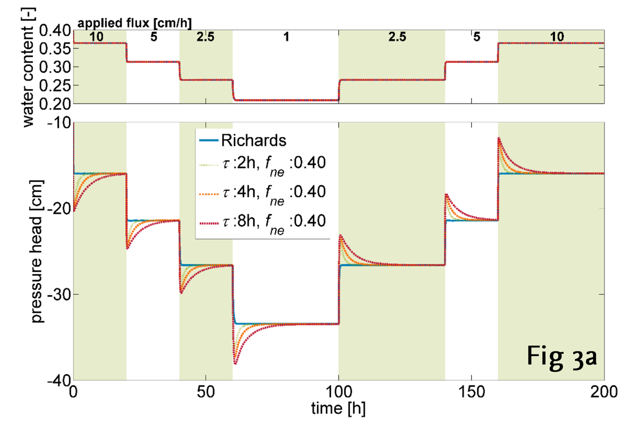
II. DNE in MSO experiments

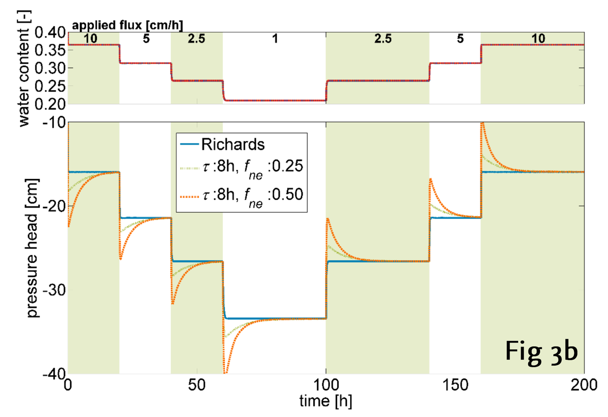




Forward simulations were conducted for a hypothetical Multistep Outflow/Inflow (MSO/MSI) experiment. The simulations were conducted with the Richards equation and for various parameters of the Dual-NE. In **Fig 2a** a sensitivity analysis for the τ parameter and in **Fig 2b** a sensitivity analysis for the f_{ne} parameter is presented. Both figures show that the Dual-NE model can represent the major observation that in the MSO/MSI experiments, the cumulative outflow data show a relaxation whereas the pressure head measured inside the soil column is at hydrostatic equilibrium. This can not be described by the Richards equation because it assumes instantaneous equilibration between the water content and the pressure head. Fitting the data of MSO experiments with the Richards equation leads to potentially wrong SHPs.

III. DNE in MSF experiments

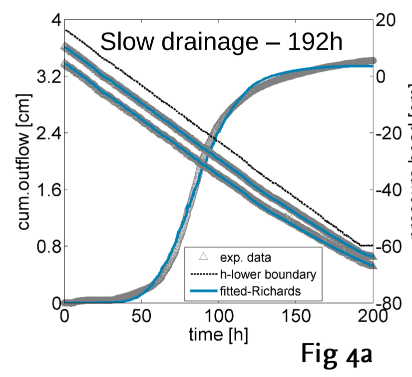




Forward simulations were conducted for a hypothetical Multistep Flux experiment for drainage and imbibition (MSFd/MSFi). The simulations were conducted with the Richards equation and for various parameters of the Dual-NE. In **Fig 3a**, a sensitivity analysis for the τ parameter is presented whereas in **Fig 3b** a sensitivity analysis for the f_{ne} parameter is presented. Both figures show that the Dual-NE model can represent the major observation that in the MSFd/MSFi experiments, after a flux change at the upper boundary and when the unit gradient conditions inside the column are achieved, the average water content inside the soil column is stable whereas the pressure head shows a relaxation toward a less negative value in the case of drainage or toward a more negative value in the case of imbibition. This can not be described by the Richards equation which assumes instantaneous equilibrium between water content and pressure head.

3. Real Data

I. Flow rate dependence of SHPs



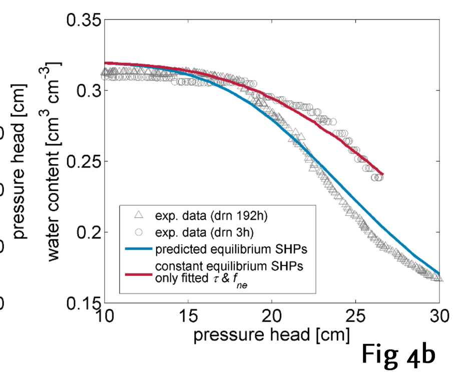


Figure 4a shows measured and fitted with the Richards equation outflow and pressure head data for a slow drainage experiment (Schultze et al., 1999). The applied pressure head at the bottom of the soil column changed smoothly from 16.7 cm to -60 cm in 192 h. **Figure 4b** shows in-situ measured water retention curves for slow (192h) and fast (3h) drainage conducted on the same soil column. The Richards equation cannot predict the measured in-situ water retention curve for the fast experiment (drn 3h) with the SHPs estimated from the slow experiment. However, keeping the SHPs from the equilibrium curves and fitting the two non-equilibrium parameters, we were able to describe the dynamic retention curve for the fast drainage experiment.

II. DNE in MSO experiments

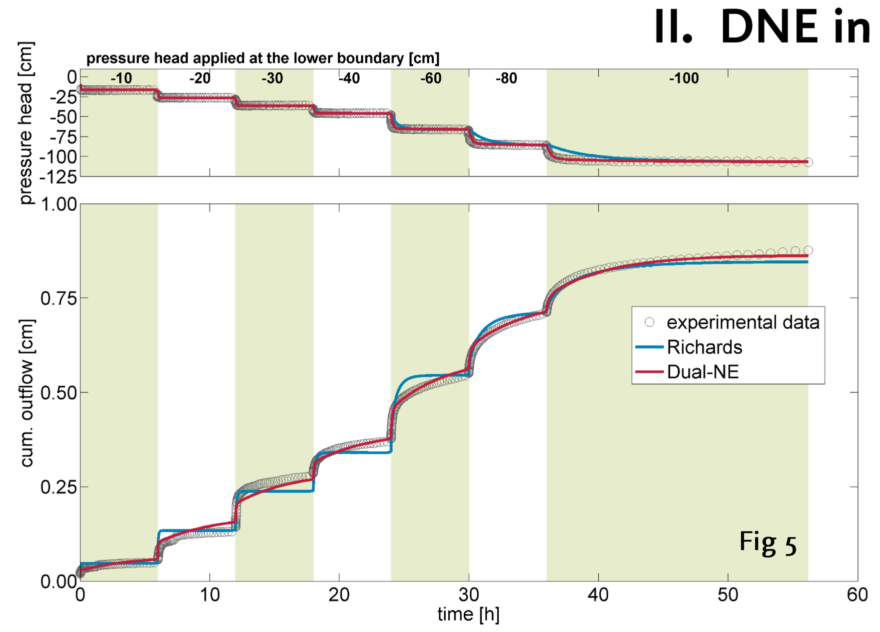


Figure 5 shows measured and fitted outflow and pressure head data for a MSO experiment for a loamy sand soil (Diamantopoulos et al. 2012, WRR). The experimental data show that after each pressure change at the lower boundary, the equilibration of the pressure head data in the column is quicker than that of the cumulative outflow data. The blue line illustrates that this cannot be described by the Richards equation since it requests simultaneous equilibration between pressure head and water content (or cumulative outflow). Accordingly, any attempt to describe the data leads to misfits. On the contrary the Dual-NE model describes both the pressure head and outflow data very well.

III. DNE in MSF experiments

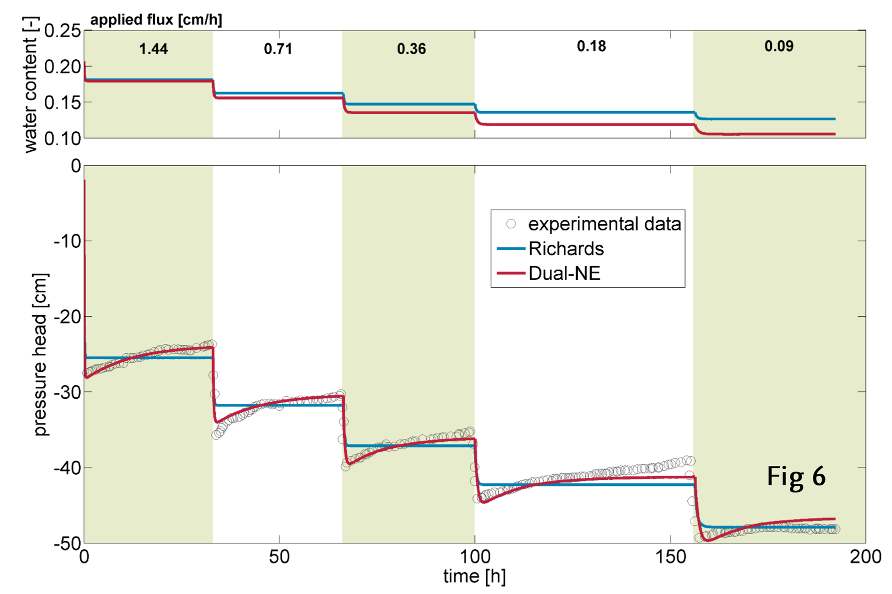


Figure 6 shows the experimental and simulated data from the study of Weller et al. (2011, VZJ). The experimental data were digitized from figure 4 in Weller et al. (2011, VZJ). Apparent is that after a stepwise change of the applied flux at the upper boundary, the pressure head drops as expected (drainage) but then it rises again to a higher value. Richards' equation predicts that after the establishment of steady-state flux with constant water content in the soil, the pressure head remains constant as well and corresponds to the one obtained from the retention curve. This contradicts the experimental findings. In contrast, the Dual-NE model predicts the observed slow equilibration of the pressure head data even if the water content remains constant.

Conclusions & Outlook

- The Dual-NE model was able to describe the three major observations of DNE effects.
- In a future work, it is important to investigate if the Dual-NE can describe DNE effects for the same soil column with the same SHPs and the same pair of non-equilibrium parameters

References

Schultze, B., O. Ippisch, B. Huwe, and W. Durner (1999), Dynamic non-equilibrium during unsaturated water flow. In: M. Th. Van Genuchten, F. J. Leij, and L. Wu. (eds.) Proc. Int. Workshop, Characterization and Measurement of the Hydraulic Properties of Unsaturated Porous Media, p. 877-892. University of California, Riverside, CA.

Acknowledgements

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