Interactive comment on "Capturing soil-water and groundwater interactions with an iterative feedback coupling scheme: New HYDRYS package for MODFLOW" by Jicai Zeng et al."

Page 4, line 98: This is the methodology you used to address the three concerns as you discussed in the introduction. I would suggest you to show a schematic showing how you address the concerns. This will help readers to get the ideas more straightforward.

Response:

We re-arranged the section 2 in correspondence of the three concerns. In first paragraph, we did an overview of these contents accordingly. Every sub-section is important to the methods developed in this paper. We hope it is straightforward and clear enough to the readers. As given in the revised manuscript (page 4, lines 99-106):

"To address the aforementioned **first concern**, governing equations for subsurface flow are given at different levels of complexity (section 2.1); numerical solution of these equations are presented (section 2.2); nonlinearity in the soil-water sub-models are reduced by a generalized switching scheme that chooses appropriate forms of the Richards' equation (*RE*) according to the hydraulic conditions at each numerical node (section 2.3); then, an iterative feedback coupling scheme is developed to solve the soil-water and groundwater models at independent scales (section 2.4). As for the **second concern**, a multi-scale water balance analysis is conducted to deal with the scale-mismatching problem at the phreatic surface (section 2.5). To cope with the **third concern**, a moving Dirichlet boundary at the groundwater table is assigned to the soil water sub-models (see Appendix A.1); the Neumann upper boundary for the saturated model is provided in Appendix A.2."

Page 6, lines 146-148: What kind of uncertainties could be as such to switch between one and another?

Response:

Switching the form of Richards' equation only matters with the soil moisture condition. As shown in Figure C1, when it is very dry, the nonlinearity in *h-form RE* is significant; while when it is near saturation, the *θ-form RE* is less effective. In our previous study (Zeng et al., 2018), there is a wide range of soil moisture state suitable for both forms of *RE*. This part of theory was not demonstrated for saving page. Readers can see more details in Zeng et al., (2018). In the revised manuscript (Page 6, lines 150-152), we stated:

"When $Se \geq Se^{crit}$, the soil moisture is closer to saturation, so the *h-form RE* is chosen as the governing equation; otherwise, when it undergoes dry soil condition, the *θ-form RE* is preferred. The empirical effective saturation for doing switching varies with soil type and is suggested to Se^{crit} = 0.4-0.9, the state when both the *h-* and *θ-form REs* are stable and efficient."

Actually, different soil has different ranges of soil moisture suitable for switching of the governing equation. Figure C1 takes a sandy soil as an example. To concise the manuscript, we prefer not to make redundant explanation how to determine the Se^{crit} of a certain soil.

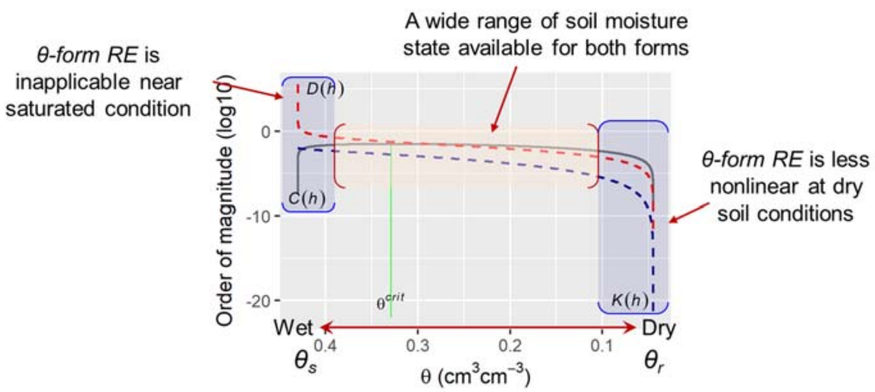

Figure C1 The soil moisture state suitable for different forms of Richards' equation. The van Genuchten model is used as the Constitutive relationship. *D*(*h*) is the hydraulic diffusivity, *K*(*h*) is the hydraulic conductivity, and *C*(*h*) is the soil moisture capacity.

Reference:

Zeng, J., Zha, Y., Yang, J., 2018. Switching the Richards' equation for modeling soil water movement under unfavorable conditions. J. Hydrol. 563, 942–949. https://doi.org/10.1016/j.jhydrol.2018.06.069

Page 7, line 164-165: how? Please offer a more specific description with details, in terms of "Space- and time-splitting strategies"

Response:

The space- and time-splitting strategies in this work, are equivalent to the scale-separation philosophy. That is, models at different scales are recognized as valid tools to describe the sub-systems, and messages at the sub-model interface are transferred within a mathematical framework. An iterative solver is usually developed to resolve the whole system. As the case in this work, the developed iterative feedback coupling "solver" solves the 1D soil water models and a 3D groundwater model at separated spatial and temporal scales. The single-scale methods in contrast, only use upscaling or downscaling approaches to unify sub-models at multiple scales, then solves them as a whole.

An example for doing space- or time-splitting should be the Multi-Scale Finite Element method (MsFEM). Generally speaking, MsFEM conducts the space-splitting mathematically at equation level. While the feedback coupling methods (e.g., the developed model) usually does such splitting physically at reservoir level. Scales are separated between the vadose and saturated zones. To avoid misleading, we corrected some statement as follows (page 7, lines 187-194)

"Space- and time-splitting strategy (see Figure 1) are adopted to separate sub-models at different scales. That is, the soil water models are established by $\Delta z = 10^{-3}$ m-10^{0} m, and $\Delta t = 10^{-5}$ d-10^{0} d; while for the saturated model, the grid sizes are $\Delta x = 10^{0}$ m-10^{3} m, and time-step sizes are $\Delta t = 10^{0}$ d-10^{1} d. Water balance at one side of the interface is conserved by scale matching of boundary conditions provided by the sub-model on the other side. For unsaturated flow, the Richards' equation requires fine discretization of space and time (Miller et al., 2006; Vogel and Ippisch, 2008); while for saturated flow, coarse spatial and temporal grids produce adequate solutions at large scale (Mehl and Hill, 2004; Zeng et al., 2017). To approximate the upper boundary flux of the groundwater flow model, a multi-scale water balance analysis is conducted within each step of the large-scale saturated flow model."

Page 7, line 174: It is recommended to put this as annex. Page 8, line 187: It is suggested to put this into annex.

Response: We moved two of these parts to the Appendix A.

Page 10, line 255: Please use a figure to indicate geometry for this case.

Response:

In the revised manuscript, we tried to clarify test case 1, rather than providing a figure for geometrical discretization. The reason is that the grids for the 1D soil models are uniform and with the same resolution (Δz = 1 cm) and spatial spread (z = 0 -1000 cm). The grid for the coupled groundwater flow is quite simple, with Δz = 500 cm for two of the layers. In the revised manuscript, we added that (page 10, lines 250-251):

"The coupled unsaturated model is discretized into a fine grid with Δz = 1 cm for solving the Richards' equation, while the saturated model is discretized into two layers with thickness of 500 cm."

Page 11, line 262: "alternately" corrected by "alternatively"

Response: Corrected. Thanks.

Pate 11, line 267: Is the moving groundwater table also considered in HYDRUS1D model? But, in this case, you only want to test soil water flow?

Response:

The moving table was not considered by a fully 1D (without coupling) HYDRUS1D model.

As added in the revised manuscript (page 10, line 239), we use case 1 to "… investigate the benefit brought by switching the Richards' equation in the unsaturated zone". That is, reducing the non-linearity in the soil water models can significantly cut down numerical cost and enhance stability when undergoing rapidly changing atmospheric upper boundaries. "The lower boundary is set non-flux to avoid the extra computational burden caused by variation of the groundwater model. Two scenarios from literature are reproduced with rapidly changing upper boundaries, as well as extreme flow interactions between the unsaturated and saturated zones (page 10, lines 241-244)". In case 1, the moving groundwater table indeed works through the simulation. With groundwater table rising from z = 200 cm to 600 cm, the length of the 1D soil column for unsaturated flow kept reducing from 800 cm to 400 cm. The moving groundwater table was caused by infiltration, rather than groundwater dynamics. The error reduction brought by moving groundwater table was discussed in test case 2.

Page 11, line 269: Please use a figure to explain the geometry you indicated here. And, this case, you only want to test the groundwater flow without considering soil water flow?

Response:

We revised the description of case 2, see page 10, lines 255-264. The schematic of case 2 is available (see Fig. 4) There are mainly two different situations with significant saturated lateral flow, i.e., sudden recharge and dynamic groundwater flow. For a quasi-3D unsaturated-saturated flow model, the unsaturated lateral flow is neglected according to its assumptions. Such assumptions are only applicable for cases with moderate infiltration, or with sudden infiltration while in very large-scale regions. Case 2 is not able to consider a very large region due to the limitation for obtaining reference solutions from a fully 2D/3D unsaturated-saturated model. A smaller region with pumping stresses is practical and demonstrative, as in case 2. The soil water upper boundary is of course applicable to increase complexity of the test case. However, it is not suggested for potentially introducing errors caused by the quasi-3D assumption in such a small-scale test, that is, the absence of unsaturated lateral flow. To better illustrate the benefits brought by using a moving Dirichlet lower boundary, the soil surface is set with the same non-flux boundary to minimize unsaturated lateral flow. In the revised manuscript, we added that (page 10, lines 255-256): "To minimize the unsaturated lateral flow, the soil surface is set with non-flux boundary." However, this doesn't necessarily mean that there is no soil water flow. The coupled model, as well as the fully-2D unsaturated-saturated model (VSF), made non-trivial efforts solving the Richards' equation in the unsaturated zone. Test case 2 successfully demonstrated the necessity for using a moving Dirichlet lower boundary when there is significant saturated lateral flow, which is common for some local events, for example, intensive pumping and autumn irrigation.

Page 11, line 277: This case, you have both irrigation and pumping, so already coupled simulation needed. But you use MODFLOW-VSF model as the "GW Truth" while HYDRUS1D as "SW Truth"?

Response:

The VSF model is indeed a fully-3D unsaturated-saturated flow model. It is quite interesting that, VSF is a model that switches the governing equation between unsaturated and saturated status. In VSF, the original 3D groundwater flow module in MODFLOW is maintained below the phreatic surface; while the 3D Richards' equation is used at and above the phreatic table. Similar application of VSF, as a fully-3D reference model, can be found in [1] *Kuznetsov, M., Yakirevich, A., Pachepsky, Y. A., Sorek, S. and Weisbrod, N.: Quasi 3D modeling of water flow in vadose zone and groundwater, J. Hydrol., 450–451, 140–149, doi:10.1016/j.jhydrol.2012.05.025, 2012.* and [2] *Twarakavi, N. K. C., Šimůnek, J. and Seo, S.: Evaluating Interactions between Groundwater and Vadose Zone Using the HYDRUS-Based Flow Package for MODFLOW, Vadose Zo. J., 7(2), 757, doi:10.2136/vzj2007.0082, 2008.* Such a fully-3D unsaturated-saturated model suffers from numerical instability and computational cost, so as the other 3D equivalents.

Page 12, line 296: Did you test the HYDRUS package for MODFLOW, with MODFLOW-VSF model results? Are

there significant difference when compared to CASE2 and CASE3?

Response:

No we didn't. The original HYDRUS package for MODFLOW has already been tested in literature (Twarakavi et al., 2008). The method was proved to be applicable for most cases without drastic flow interaction at the water table. The advantages of the developed method are illustrated by cases 1, 2, and 3. Under this condition, case 4 reproduced a benchmark synthetic case for regional application, which has already been substantially tested by *Twarakavi, N. K. C., Šimůnek, J. and Seo, S.: Evaluating Interactions between Groundwater and Vadose Zone Using the HYDRUS-Based Flow Package for MODFLOW, Vadose Zo. J., 7(2), 757, doi:10.2136/vzj2007.0082, 2008.* In their study, such a regional problem was simulated by the REC-ET, MODFLOW-UZF1, and the original HYDRUS package for MODFLOW. It was technically impossible to provide an accurate fully-3D truth solution for such a large region during such a long simulation period. In the same way therefore, we took the results from equivalent methods (original Hydrus package for MODFLOW) as a potential reference solution. Besides, the applicability of the developed method for practical use are presented. The codes, as well as inputs and outputs, are available from paper Twarakavi et al., (2008) and the references therein.

Page 12, line 300: Delete "soil water retention curve"

Response:

The nonlinearity in soil water models are one of the concerns we addressed during the discussion. So we changed this sentence into "the non-linearity of the soil water models…" (see page 11, lines 289-290)

Page 12, line 310: Change "allowable" into "acceptable"

Response:

Corrected.

Page 25, Fig 1, The figure is blurred not clear to be seen. It is lacking of description in terms of how coupling happens.

Response:

We rebuilt the figures and made detailed description of them. See Fig. 1 in page 25.

Page 26, Fig 2: Again, a more detailed explanation is needed, other than just showing the figures. The figure is again blurred and need to be updated with high quality images.

Response:

The figures are replaced with higher resolution. Detailed descriptions are presented. See Fig 2. In Page 26.