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."

This paper developed the switching method of h- and θ-form of Richards equation to lower the non-linearity in the soil-water and groundwater coupling system and the iterative feedback coupling scheme to reduce the coupling errors. Four numerical cases were employed to address three concerns arose using the iterative feedback coupling method.

This work tries to find the tradeoff between the modeling accuracy and the computational cost of the soil-water and groundwater coupling system. The method presented here seems promising in the application of large scale problems. Nevertheless, I have some concerns about the 'real' modeling accuracy when using the proposed method. You took the simulation results of HYDRUS1D, MODFLOW-VSF (Thoms et al., 2006), and HYDRUS package for MODFLOW (Seo et al., 2007) as the 'truth'. Thus, when you compare the simulation results of the proposed method and the "truth"(e.g., Figure 7), it is difficult to determine which method is better.

The paper is well written and structured. Some suggestions are detailed as below.

Response:

Thank you for your comments. The "truth" is not always easy to find. The regional-scale fully-3D solution with high-density discretization is extremely very difficult to obtain (Niswonger and Prudic, 2009). In relevant literature, the 3D Richards' equation has been regarded as a painstaking truth. That was also the reason we turned to a quasi-3D scheme to approximate regional solution. Although various quasi-3D schemes were developed to reduce the total complexity and numerical difficulty, a tradeoff between cost and benefit was what we mainly concerned. To address three of the problems arose when doing quasi-3D coupling, we carefully designed different scenarios in the fully-1D/2D/3D benchmark problems.

Firstly, the efficiency improvement brought by switching the Richards' equation was illustrated with rapidly changing atmospheric upper boundaries upon a 1D soil column. To avoid extra CPU time consumption that were caused by more complicated conditions in the saturated domain, only the upper boundary was in function. As a matter of fact, making the benchmark problem more complicated in the saturated part, will inevitably exaggerate the benefits brought by switching the Richards' equation. The reason is that, when the coupling model suffers from more non-linearity at two sides of the coupling interface, more feedback iterations will be needed. Thus, the percent of CPU cost in the unsaturated zone will increase, which may overstate the advantages in the switching RE method.

Secondly, the error reduction by using the iteratively two-way coupling scheme was demonstrated with the 1D and 3D cases. In the 1D cases, the iterative coupling scheme was regulated by adjusting the closure criteria and maximal number of feedback iterations. Three times of feedback iterations with linearly predicted groundwater table were proved to be reasonable to achieve sound convergence of the problem. The optimum number of 1D soil columns for a 3D regional case was suggested to be as less as possible.

Thirdly, the accuracy improvement by the moving-balancing-domain approach were presented in the 2D case. The dynamically changing groundwater table was designed to better illustrate the significance of the saturated lateral flow in a quasi-3D coupling scheme. That is, when using a moving lower boundary for the balancing domain, the need for extra analysis of the water input from the saturated part was avoided successfully. Such improvement was illustrated by using different lengths of soil columns in the 2D test case. For simplicity, the soil-surface boundary was set non-flux. A more complicated upper boundary in the unsaturated zone, e.g. local infiltration, would of course add to the demonstration of such a pumping test. However, it would increase the solution errors in the unsaturated zone, which originates from the basic quasi-3D assumptions. To avoid the error superposition from the unsaturated and saturated zones, the 2D test case was carefully designed with only saturated stresses.

Finally, to demonstrate the applicability of the developed model for complex regional problems, a synthetic case from literature was revisited. The truth solution was not easy to obtain, so we compared the results with the original

HYDRUS package for MODFLOW, as was done in relevant literature (Shen and Phanikumar, 2010; Twarakavi et al., 2008; Xu et al., 2012; Zhu et al., 2012). The purpose of this case study (case 4) was not to tell the accuracy improvement of the developed method, but to show its applicability for practical use.

Based on the above, the purposes and results of the test cases are further explained in the revised manuscript. Specifically, figure 7 of is the validation of the coupling model, other than the advantage of the method against one another.

References:

Niswonger, R.G., Prudic, D.E., 2009. Comment on "Evaluating Interactions between Groundwater and Vadose Zone Using the HYDRUS-Based Flow Package for MODFLOW" by Navin Kumar C. Twarakavi, Jirka Šimůnek, and Sophia Seo. Vadose Zo. J. 8, 818. https://doi.org/10.2136/vzj2008.0155

Shen, C., Phanikumar, M.S., 2010. A process-based, distributed hydrologic model based on a large-scale method for surface - subsurface coupling. Adv. Water Resour. 33, 1524–1541. https://doi.org/10.1016/j.advwatres.2010.09.002

Twarakavi, N.K.C., Šimůnek, J., Seo, S., 2008. Evaluating Interactions between Groundwater and Vadose Zone Using the HYDRUS-Based Flow Package for MODFLOW. Vadose Zo. J. 7, 757. https://doi.org/10.2136/vzj2007.0082

Xu, X., Huang, G., Zhan, H., Qu, Z., Huang, Q., 2012. Integration of SWAP and MODFLOW-2000 for modeling groundwater dynamics in shallow water table areas. J. Hydrol. 412–413, 170–181. https://doi.org/10.1016/j.jhydrol.2011.07.002

Zhu, Y., Shi, L., Lin, L., Yang, J., Ye, M., 2012. A fully coupled numerical modeling for regional unsaturated-saturated water flow. J. Hydrol. 475, 188–203. https://doi.org/10.1016/j.jhydrol.2012.09.048

Title: HYDRYS → HYDRUS

Response:

Thanks. It is revised.

Line 108: soil capacity → soil water capacity

Response:

All of the misused terms were revised. See lines 111 and 146.

Line 148: " ⋯ is suggested to 0.4-0.9" → " ⋯ is suggested to be 0.4-0.9"

Response:

It is revised. See line 152.

Line 163-167 (Figure 1): the space- and time-splitting strategies should be illustrated in a more detail way. You said that coupling models at different scales should deal with the inconsistency in spatial and temporal discretization, however, there is not too much context illustrate how such inconsistency was handled in your coupling system.

Response:

Thanks. We agree. The illustrative context for Figure 1 was further provided in lines 186-, as well as in the figure caption (see line 605 in page 26).

Line 253-254: there is no C_i and Δz_i in Eqn. 20. The description of C_i and Δz_i seems redundant.

Response:

We deleted that. Sorry for misleading.

Figure 6: what is the difference between coupled h-form RE and HYDRUS1D?

Response:

In this case, the *h-form RE* in the two-way coupling model is used to better illustrate the high performance in the Switching RE. Both forms of RE were incorporated into a two-way coupling scheme. However, it is not necessary and interfering. We removed this part of comparison, see the newly updated Figure 7 in page 31.

Section 4.2: You use both the "Cumulative mass balance errors" and "coupling errors" in the section 4.2 multi-scale water balance analysis, is there any difference between these two terms?

Response:

Sorry for misleading. In this work, the *cumulative mass balance errors* are equivalent to the *coupling errors*, and are exactly what we wanted to reduce with the developed method. We unified it into *coupling errors*, see line 320.

Figure 8: On the basis of the truth, three different methods (stepwise method, iteratively linear method, and non-iteratively linear method) were compared in Figure 8. What kind of method was used for the 'truth' (HYDRUS1D)?

Response:

HYDRUS1D is theoretically not a coupling model for unsaturated and saturated flows. It does not need any prediction of the Dirichlet lower boundary, including stepwise, linear extension, and etc. Differences among three of the coupling methods, stepwise, iteratively linear, and non-iteratively linear, were about how the 3D groundwater model (MODFLOW) provided Dirichlet lower boundary for the 1D unsaturated sub-models. To find out the "truth", the HYDRUS1D solution, which was obtained without any coupling between the unsaturated and saturated sub-domains. So no such coupling method was used in HYDRUS1D. We used the 1D test case to better illustrate how did the (non-)iteratively linear method functioned as an approximation towards the "truth".

Line 373: ε_F = 20 m/d or 20cm/d?

Response:

We revised it into $\varepsilon_F = +\infty$, see line 364. Different combinations of ε_H and ε_F had some effect on the cost-benefit discussion. For example, the group of (ε_H, ε_F) = (0.1 cm, 0.01 cm/d) or (0.01 cm, 0.1 cm/d) may lead to similar closure errors. In case of such interference, we opened one of them. That is, only ε_H was changed from 0.001 cm to 20 cm in the comparative analysis, while ε_F is set by $+\infty$, which was not possible in real case.

Line 406: (Twarakavi et al., 2008) → Twarakavi et al. (2008)

Response:

Thanks, we revised it.

Line 408: You should clear present the results of figures in the context, not just say "Figure 13b presents the absolute head difference of the method developed here and the HYDRUS package at the end of stress periods 3, 6, 9, and 12."

Response:

The discussion of the figures was rephrased. See lines 395-399.

Figure 14: sub-zones 1, 3, 5, 7, 9 or sub-zones 1, 5, 9, 13, 20?

Response:

We corrected it.