Vadose Zone Journal Reply

Reply to "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

Navin Kumar C. Twarakavi,* Jirka Šimůnek, and Sophia Seo

Niswonger and Prudic (2009) commented on the comparison of the UZF1 (Niswonger et al., 2006) and HYDRUS (Seo et al., 2007) packages and their ability to incorporate vadose zone flow processes into the MODFLOW model, presented in our manuscript (Twarakavi et al., 2008). Niswonger and Prudic's (2009) comments give us an opportunity to better clarify the objectives of our paper (Twarakavi et al., 2008). Our main objective was to introduce the HYDRUS package for MODFLOW as another option for modeling coupled vadose zone and groundwater fluxes with the existing approaches, such as the REC-ET, VSF (Thoms et al., 2006), and UZF1 packages. Twarakavi et al. (2008) concluded that because the HYDRUS package can account for depth-dependent root water uptake, water fluxes in both downward and upward directions, and multiple soil horizons with varying hydraulic properties, while the UZF1 package considers only homogeneous soil profiles, the "HYDRUS package thus offers a good alternative to the UZF1 package when these factors, e.g., vegetation or multiple horizons, are significant for a particular application."

First, Niswonger and Prudic (2009) note that the UZF1 package allows for groundwater discharge to the land surface (such as a stream or a lake) whenever the water table in a particular cell exceeds the land-surface elevation. It is true that the current version of the HYDRUS package does not address this process, since its main objective is to account for flow in the unsaturated zone. On the other hand, the HYDRUS package implements an "atmospheric" boundary condition for the upper boundary, which allows rainfall or irrigation water in excess of the soil infiltration capacity to either accumulate at the soil surface and create a dynamic surface water layer or generate surface runoff. We believe that the HYDRUS package also handles evapotranspiration, an important process of water discharge through the land surface that can be particularly important under shallow water tables conditions, better. While the UZF1 package estimates evapotranspiration losses as a function of the extinction depth using a simple empirical function that may not always represent this complex process correctly, the HYDRUS package can better approximate it by solving the Richards equation and can even simulate capillary rise. Depth-dependent calculations of water loss by evapotranspiration used in the UZF1 package are a very rough approximation of this highly nonlinear process, which the HYDRUS package can handle more rigorously.

Next, Niswonger and Prudic (2009) point out that the computational speed of the UZF1 package for the "Case Study 3: Hypothetical Regional-Scale Groundwater Problem" in Twarakavi et al. (2008) can be greatly improved and, as a result, UZF1 can generate results faster than the HYDRUS package. Niswonger and Prudic (2009) note that when discretization of drainage waves is reduced from 25 (used in Niswonger et al., 2006) to 10 increments, the UZF1 package runs two times faster than HYDRUS. As in Niswonger et al. (2006), the HYDRUS package simulation of this case study was simply intended to illustrate the applicability of this package to larger scales without either greatly compromising the computational speed of the overall system or optimizing spatial and temporal discretization. We would also be able to significantly reduce the required computational time by (i) using coarser discretization of the HYDRUS soil profiles, (ii) decreasing the number of zones, (iii) using coarser temporal discretization, and/or (iv) reducing internal iteration criteria. However, it is our belief that it is preferable to use finer discretizations and stricter convergence criteria, thus guaranteeing a proper description of flow processes, to optimize computation speed. We agree with Niswonger and Prudic (2009) regarding the need to demonstrate the applicability of the HYDRUS package to a realistic watershed-scale problem. Since that was beyond the scope of the paper under discussion, we intend to present a few computationally demanding and realistic case studies in the public library of HYDRUS examples on the HYDRUS Web site in the near future (http://www.pc-progress.com/en/Default.aspx?h1d-library).

Niswonger and Prudic (2009) also noted that they do not agree with the "assumption that HYDRUS's method for simulating one-dimensional unsaturated flow through layered sediment is more applicable than assuming an effectively homogeneous unsaturated zone." Even though the current state of practice in groundwater flow modeling still considers uniform overlaying

N.K.C. Twarakavi, Dep. of Agronomy and Soils, Auburn Univ., Auburn, AL 36849; J. Šimůnek, Dep. of Environmental Sciences, Univ. of California Riverside, Riverside, CA 92521; S. Seo, Colorado School of Mines, 1500 Illinois St., Golden, CO 80401. *Corresponding author (twarakavi@auburn.edu).

Vadose Zone J. 8:820–821
doi:10.2136/vzj2008.0004L

soils in the vadose zone, we believe that this should not remain the status quo and that this simplification hampers the advancement of research in ground water modeling. While we agree that detailed information on layering may not always be available and that considering numerous layers in such cases may not be feasible, in situations where such information is available, it may be beneficial to consider. Most soil profiles conform to a pattern of horizons that should be considered to improve the reliability of calculated vadose zone fluxes. Further, Niswonger and Prudic (2009) indicate that the HYDRUS package's inability to simulate lateral spreading in the unsaturated zone renders consideration of layering ineffective. We agree that no model that considers only one-dimensional vertical flow can be effective for conditions where lateral spreading (e.g., in perched water layers) in the unsaturated zone is a process significantly affecting groundwater recharge. For conditions where these processes need to be considered, fully three-dimensional models, such as VSF (Thoms et al., 2006) or HYDRUS (2D/3D) (Šimůnek et al., 2006), should be used. The HYDRUS package, which obviously can consider homogeneous conditions, is meant to be a tool for use when an assumption of one-dimensional flow in the vadose zone is reasonable. It is up to users of the HYDRUS package to decide whether to consider layering or opt out for a homogeneous description of the vadose zone. We note here that almost all widely used one-dimensional models simulating water flow and solute transport in the vadose zone currently do consider soil layering, and that a model without such an option would likely be rejected by both researchers and the practicing community.

Further, Niswonger and Prudic (2009) commented on water balance with regard to the HYDRUS package. The HYDRUS package for MODFLOW maintains the water budget during simulations. The HYDRUS package considers the exact distribution of water contents above the groundwater as a solution of the Richards equation (reflecting different textures and retention curves), which is obtained using a mass-conservative numerical scheme, thereby maintaining a sound mass balance. The mass balance for the HYDRUS package simulations is outputted when required by the user for verification purposes. Similarly, MODFLOW itself reports the mass balance when required by the user. There is obviously a slight inconsistency between MODFLOW that represents the vadose zone by a constant, that is, a "specific yield," while HYDRUS uses a complete description using full definition of retention curves. However, since both models report their mass balances, the user has complete information about it. In cases where the coupled mass balance is not achieved satisfactorily, we would like to note that a version of the HYDRUS package is available that can attain a complete mass balance between the saturated and unsaturated zones by suitably altering the unsaturated profiles for each zone at the end of each time step. However, it is recommended that this version of the HYDRUS package should only be used on a case-by-case basis.

We agree with Niswonger and Prudic (2009) that the numerical stability, or the lack of such stability, in the HYDRUS package will play an important role in its successful adoption by research or the practicing community. The numerical stability of models based on the numerical solution of the Richards equation still depends partly on a proper selection of spatial and temporal discretization and related iteration criteria, and thus on the experience of their users. For this reason, we exert a great effort, in addition to model development, in training HYDRUS users (short courses, online tutorials) or providing them with information (see, e.g., the public library of HYDRUS projects at http://www.pc-progress.com/en/Default.aspx?h1d-library) on how to successfully use our models. The hundreds of successful applications of HYDRUS models appearing in peer-reviewed literature (Šimůnek et al., 2008) (and likely many more unreported) offer proof that we are on the right track and that the issues associated with numerical instability can be overcome.

Although the UZF1 package has been proven to work in some case studies (Niswonger et al., 2006), since the package is based on the Kinematic wave approach, which assumes that variably saturated water flow is driven exclusively by gravitational potential, and ignores the effect of capillary and other forces, it provides a poorer characterization of water flow in the vadose zone than approaches based on the Richards equation. In addition, more research and characterization of water flow in the vadose zone in various soils have been performed using the Richards equation than the Kinematic wave approach. We believe that coupling the one-dimensional Richards equation–based package to MODFLOW balances computational speed and model efficiencies at different scales and represents a step in the right direction.

Acknowledgments

The activities on which this report is based were financed in part by the Department of the Interior, U.S. Geological Survey, through The Regents of the University of California and the UC Center for Water Resources.

References

Niswonger, R.G., and D.E. Prudic. 2009. Comment on "Evaluating interactions between groundwater and vadose zone using the HYDRUS-based flow package for MODFLOW." Vadose Zone J. 8:818–819 (this issue).

Niswonger, R.G., D.E. Prudic, and R.S. Regan. 2006. Documentation of the unsaturated-zone flow (UZF1) package for modeling unsaturated flow between the land surface and the water table with MODFLOW-2005. Techniques and Methods 6-A19. Available at http://pubs.usgs.gov/tm/2006/tm6a19/ (verified 13 May 2009). USGS, Denver, CO.

Seo, H.S., J. Šimůnek, and E.P. Poeter. 2007. Documentation of the HYDRUS package for MODFLOW-2000, the U.S. Geological Survey modular ground-water model. GWMI 2007-01. Int. Ground Water Modeling Ctr., Colorado School of Mines, Golden, CO.

Šimůnek, J., M.Th. van Genuchten, and M. Šejna. 2006. The HYDRUS software package for simulating two- and three-dimensional movement of water, heat, and multiple solutes in variably saturated media. p. 241. *In* Technical manual, version 1.0. PC Progress, Prague, Czech Republic.

Šimůnek, J., M.Th. van Genuchten, and M. Šejna. 2008. Development and applications of the HYDRUS and STANMOD software packages, and related codes. Vadose Zone J. 7:587–600.

Thoms, R.B., R.L. Johnson, and R.W. Healy. 2006. User's guide to the variably saturated flow (VSF) process for MODFLOW. Techniques and Methods 6-A18. Available at http://pubs.usgs.gov/tm/2006/tm6a18/ (verified 13 May 2009). USGS, Reston, VA.

Twarakavi, N.K.C., J. Šimůnek, and S. Seo. 2008. Evaluating interactions between groundwater and vadose zone using the HYDRUS-based flow package for MODFLOW. Vadose Zone J. 7:757–768.