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A hybrid finite volume-finite element model for the numerical analysis of furrow irrigation and fertigation

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ABSTRACT

This study presents a hybrid Finite Volume – Finite Element (FV-FE) model that describes the coupled surface-subsurface flow processes occurring during furrow irrigation and fertigation. The numerical approach combines a one-dimensional description of water flow and solute transport in an open channel with a two-dimensional description of water flow and solute transport in a subsurface soil domain, thus reducing the dimensionality of the problem and the computational cost. The modeling framework includes the widely used hydrological model, HYDRUS, which can simulate the movement of water and solutes, as well as root water and nutrient uptake in variably-saturated soils. The robustness of the proposed model was examined and confirmed by mesh and time step sensitivity analyses. The model was theoretically validated by comparison with simulations conducted with the well-established model WinSRFR and experimentally validated by comparison with field-measured data from a furrow fertigation experiment conducted in the US.

1. Introduction

Agriculture is among the most important human activities due to its role in the food supply chain. According to one of the latest FAO reports (FAO, 2017), agricultural production more than tripled between 1960 and 2015. This remarkable expansion has been accompanied with a dramatic increase in the use of irrigation and fertilization, and an associated significant environmental footprint, thus posing important sustainability issues. Irrigation for agricultural purposes accounts for 70% of all water withdrawn from aquifers, lakes, and streams (FAO, 2011a). Furthermore, the worldwide demand for fertilizers has grown by 25% in the last decade, and this trend is expected to continue in coming years (FAO, 2015), increasing the risk of nutrient pollution of water bodies. Thus, the transition towards more efficient and sustainable irrigation and fertigation strategies is necessary.

Although slowly replaced by pressurized irrigation in developed regions such as The United States, Europe, and Israel, surface irrigation systems continue to be a preferred irrigation method in developing countries. In 2011, surface systems accounted for 96.8% of irrigated surfaces in Southern and Eastern Asia (FAO, 2011b). In particular, basin and furrow irrigation were the most widespread techniques among farmers. When correctly performed, furrow fertigation can increase the efficiency of fertilizer use and crop fertilizer uptake, compared to traditional techniques (Fahong et al., 2004; Horst et al., 2005; Siyal et al., 2012; Šimůnek et al., 2016a). To be successful, furrow irrigation and fertigation systems should be designed and managed so that the application and distribution of water and fertilizer are efficient and uniform, with minimal surface runoff at the lower end of the field and with minimal deep drainage and leaching below the crop root zone (Šimůnek et al., 2016a). To optimize the performance of furrow irrigation systems, numerical models may play an important role since they represent powerful tools for assessing irrigation and fertigation efficiency.

Furrow irrigation and fertigation are coupled surface-subsurface processes. Water and solute are injected at the soil surface at one side of an open channel, hence generating a sharp front that moves along a furrow while water and nutrients infiltrate in the underlying soil. Therefore, furrow irrigation and fertigation are (physically, mathematically, and numerically) described as coupled three-dimensional flow and transport processes in both surface and subsurface domains. Nevertheless, solving a fully coupled system of 2D Shallow Water and 3D Richards equations would require significant computing resources and would also likely pose substantial stability issues, mainly stemming from the high nonlinearity of the governing equations. This presents a problem in the modeling of flooding and drying processes over porous beds.

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Therefore, several models have been proposed in the literature that reduce the numerical complexity of a fully 3D model. Katopodes and Strelkoff (1977) used a dimensionless formulation of the governing equations to show that when the Froude number is small, which is typical under irrigation conditions, the inertial terms in the shallow water equations are negligible. With this in mind, they developed the first zero-inertia model for irrigation (Strelkoff and Katopodes, 1977). In the early 80s, Walker and Humpherys (1983) proposed a furrow irrigation model based on a 1D kinematic wave (KW) approximation of open channel flow coupled with the modified Kostiakov equation describing the infiltration process. While the model was assessed against experimental data with satisfactory results, the adoption of the KW equation limited its application to open-ended furrows. Furthermore, the model did not include any description of the subsurface water dynamics. Later on, Oweis and Walker (1990) replaced the KW approximation with the one-dimensional (1D) zero-inertia (ZI) equation, which represents a more realistic approximation of the Shallow Water equations. A more detailed fertigation model was first proposed by Abbasi et al. (2003) and later improved by Perea et al. (2010). In these two studies, water flow and solute transport in an open channel were described using the 1D Zero-Inertia and advection-dispersion equations, respectively. The modified Kostiakov equation was used to calculate infiltration at each time step. Although the model was verified with good results against experimental data from four experimental sites, subsurface flow processes were again neglected.

To provide a better and more complete description of coupled water flow and solute transport in the soil, several other models have been proposed in the literature. For example, Zerihun et al. (2005) coupled the 1D zero-inertia equation with the HYDRUS-1D model (Šimůnek et al., 2016b), which numerically describes water flow and solute transport as well as root water and nutrient uptake in 1D variably-saturated porous media. The computational framework, which targeted basin irrigation, was based on the iterative coupling between the surface and subsurface models and was validated against measured data with good results. Ebrahimian et al. (2013) extended this concept to furrows by coupling a 1D furrow fertigation model with the two-dimensional HYDRUS-2D model (Šimůnek et al., 2016b). The coupled model satisfactorily reproduced the overland transport as well as the solute transport in the soil profile. However, the surface and subsurface components were solved separately, leading to an *uncoupled* numerical framework. As pointed out by Furman (2008), theoretically, the higher the level of coupling, the higher the solution accuracy. This is mainly due to the high nonlinearity of the involved processes, as well as to their different time scales. For instance, overland flow is generally faster than infiltration, thus requiring a different temporal resolution. This temporal misalignment poses significant numerical issues since an approximation is needed to couple surface and subsurface flow. The accuracy of this approximation strongly influences the conservativeness of the numerical scheme. Similarly, the overland solute transport needs to be solved simultaneously with water flow in order to preserve the monotonicity of the solution.

One of the most complete furrow irrigation models was developed by Wöhling et al. (2004). The proposed computational framework iteratively coupled a 1D analytical zero-inertia equation with HYDRUS-2D, thus providing a complete description of surface-subsurface water flow along the furrow. The model was further developed and extended by Wöhling et al. (2006), Wöhling and Mailhol (2007), and Wöhling and Schmitz (2007). A similar approach was used by Tabuada et al. (1995), who coupled a model based on a complete hydrodynamic equation of overland flow with a two-dimensional Richards equation. While accurately simulating water flow, neither of the models discussed above considered solute transport in surface and subsurface domains, thus restricting their applicability to irrigation. Hence, further development of similar approaches that would include a detailed description of solute transport in the root zone is desirable for both scientists and practitioners (Ebrahimian et al., 2014).

Most of the existing furrow irrigation models adopt a Lagrangian approach, which uses a computational grid that moves along with the wet/dry interface. Although elegant and accurate, this type of approach can lead to coupling issues between the surface and subsurface models, mainly because the grid must be regenerated each time the wet/dry interface moves, and the computational nodes often must be added during flooding or removed during recession to reduce grid distortion error. However, while surface processes are discontinuous (surface flow and transport occur only during irrigation events), subsurface processes are continuous (subsurface flow and transport continues between irrigation events). Therefore, a fix grid for the subsurface domain is usually used, and values of interest (e.g., infiltration, soil moisture, pressure head, etc.) need to be interpolated between surface nodes, thus leading to a hybrid Lagrangian-Eulerian approach. Nevertheless, results have proven to be fairly sensitive to the interpolation strategy (Wöhling et al., 2006). Lazarovitch et al. (2009) applied the moment analysis techniques to describe the spatial and temporal subsurface wetting patterns resulting from furrow infiltration and redistribution. Furthermore, most of the existing models are based on the finite difference method (e.g., Tabuada et al., 1995; Abbasi et al., 2003; Perea et al., 2010), which can yield spurious oscillations at flow discontinuities unless first-order accurate (upwind) schemes or artificial dissipation are employed.

Godunov-type Finite Volume (FV) schemes have been successfully applied to simulate overland flow over pervious and impervious lands (Bradford and Katopodes, 2001; Bradford and Sanders, 2002; Brufau et al., 2002; Burguete et al., 2009; Dong et al., 2013). The FV schemes solve the integral form of the overland flow and solute transport equations, thus being mass conservative both globally and locally. Numerical fluxes are evaluated at the cell faces, thus guaranteeing a straightforward and efficient treatment of the dry bed problem by allowing for flooding and drying of fixed computational cells. Furthermore, numerical oscillations near discontinuities can be eliminated using flux limiters (Bradford and Katopodes, 2001). However, their application to furrow irrigation and fertigation has been rather limited and has not involved a coupled mechanistic description of the subsurface domain.

Thus, the main goal of this study is to develop and validate a hybrid Finite Volume-Finite Element (FV-FE) reduced-order model capable of describing coupled surface-subsurface flow and transport processes involved in furrow fertigation. The proposed numerical approach combines a one-dimensional FV description of coupled water flow and solute transport in the surface domain with a two-dimensional mechanistic FE description of flow and transport in the variably-saturated zone, thus reducing the dimensionality (3D) of the problem and associated computational cost. The modeling framework includes the widely-used FE model, HYDRUS-2D, whose numerical features significantly increased the overall modeling flexibility. The proposed model is the first attempt to include HYDRUS-2D in a coupled surface-subsurface furrow fertigation model, thus representing a new contribution to this field. The problem is addressed in the following way. First, the hybrid FE-FV model is theoretically validated against the well-established model WinSRFR (Bautista et al., 2009) using synthetic validation scenarios. Preliminary mesh and time step sensitivity analyses are performed to evaluate the accuracy and the robustness of the proposed numerical approach. Next, the model is validated against measured data from an experimental facility in California, US.

2. Materials and methods

2.1. Modeling approach

The proposed approach combines a one-dimensional description of coupled water flow and solute transport in an open channel with a two-dimensional description of variably-saturated water flow and solute transport in soil. As in previous studies (e.g., Tabuada et al., 1995;