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Quasi 3D modelling of vadose zone soil-water flow for optimizing irrigation strategies: Challenges, uncertainties and efficiencies

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ABSTRACT

A quasi 3D modelling approach was developed by integrating a crop growth (LINGRA-N) and a hydrological model (Hydrus-1D) to simulate and visualize water flow, soil-water storage, water stress and crop yield over a heterogeneous sandy field. We assessed computational efficiency and uncertainty with low- to high-spatial resolution input factors (soil-hydraulic properties, soil-layer thickness and groundwater level) and evaluated four irrigation scenarios (no, current, optimized and triggered) to find the optimal and cost-effective irrigation scheduling. Numerical results showed that the simulation uncertainty was reduced when using the high-resolution information while a fast performance was maintained. The approach accurately determined the field scale irrigation requirements, taking into account spatial variations of input information. Optimal irrigation scheduling is obtained by triggered-irrigation resulting in saving up to ~300% water as compared to the current-irrigation, while yield increased ~1%. Overall, the approach can be useful to help decision makers and applicants in precision farming.

1. Introduction

Soils are intrinsically heterogeneous, and so are the hydraulic properties that control the ability of soil to store and conduct water at the field scale. Additionally, spatial and temporal variations of boundary conditions (groundwater level (GWL) at the lower boundary and evapotranspiration at the upper boundary), and topography considerably affect soil-water content variability, water flow and thus crop water availability and yield at the field scale. Efficient techniques to characterize soil physical variability remain the object of scientific pursuit (Teixeira et al., 2014). Modern technologies such as automated soil sensors and tensiometers, can quantify flow processes and soil-water status but only at a limited number of sites, mostly because of labor and cost requirements (Bastiaanssen et al., 2004). As an alternative, advanced numerical modelling for simulating hydrological processes through the vadose zone and understanding the interaction between soil, vegetation, atmospheric forcing and groundwater (Bastiaanssen et al., 2007; Šimůnek et al., 2016) can be carried out to control soil water status and irrigation -heterogeneous distribution of water under different field conditions-in precision agriculture.

In the modelling framework, due to the complexity of flow systems, a variety of conceptual simplifications have been made to flow models. Such simplifications include e.g. the assumption of water movement in the unsaturated zone as a one-dimensional phenomenon, by considering i) lateral flow and transport as not significant (Antonopoulos and Wyseure, 1998; Kuznetsov et al., 2012; Sherlock et al., 2002; Tian et al., 2012) unless the capillary fringe is involved (Abit et al., 2008); ii) a simple representation of the bottom boundary condition using a constant or unit-gradient (Canone et al., 2015; Carrera-Hernández et al., 2012) or perched saturated layers (Twarakavi et al., 2009); iii) effective homogeneity within and between soil layers (Niswonger and Prudic, 2009) and isotropy of hydraulic properties; iv) the porous matrix as rigid and water density not dependent on solute concentration and temperature (Kuznetsov et al., 2012); and vi) similar micro-climate for initial and upper boundary for different parts of the field or region. In addition, evaluation of the uncertainty and sensitivity of the models by performing multiple simulations at different scales or

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resolutions, investigation of the cost effectiveness of simulation times (pre and post processing), and application of an approach to optimize irrigation management are the challenging issues.

From a field to a regional water management perspective, the most important challenge in numerical modelling is to fully model the water flow (unsaturated and saturated flows from the soil surface to groundwater) in a spatially variable context. In addition, generalizing field scale water application based on the results of modelling approach at the plot scale (1D) (i.e., only one spot), is subjected to significant uncertainty. During past decades, a bulk of efforts has been made to develop numerical models, i.e., fully three-dimensional (3D) codes (Arnold et al., 1993; Saxton et al., 1974; Šimůnek et al., 2006; Therrien et al., 2009; van Dam et al., 1997) and new approaches such as coupling/integrating existing coded modelling concepts (2D or quasi 3D modelling) to simulate water flows in the vadose zone and saturated-unsaturated interactions (Cartwright et al., 2006; Kuznetsov et al., 2012; Refsgaard and Storm, 1995; Twarakavi et al., 2008; Zhu et al., 2012) and in irrigation management (Condon and Maxwell, 2013; Perez et al., 2011; Wu et al., 2015; Zhu et al., 2012). Despite simplifications and assumptions, they are usually computationally most expensive, particularly 3D tools which are not suitable for modelling large field water problems, as well as in terms of parameterization, uncertainty and sensitivity evaluations (Condon and Maxwell, 2013; Kuznetsov et al., 2012).

The combination of accurate and spatially distributed field data with appropriate numerical models will allow to accurately determine field scale water flow and thus field scale irrigation requirements, taking into account the information gained at the plot scale (1D), variations in boundary conditions across the field and spatial variations of model parameters (Rezaei et al., 2016b). Therefore, it is important to develop an approach that can efficiently simulate field scale water flow. In such case, a quasi 3D modelling approach (2D approach) can be used to apply 1D simulations to cover the field scale (Rezaei et al., 2016b).

This paper focuses on the development of a field scale soil hydrological model (coupled with a crop growth model) to predict soil-water content, water stress, and crop yield based on a representation of the field as a bundle of 1D soil columns with varying hydraulic properties and boundary conditions. The approach is similar to the approach presented by Joris et al. (2014) in which the Hydrus-1D model was applied to simulate contaminant leaching/transport for the Belgian-Dutch transnational Kempen region (200×200 m resolution). But overall, it differs from the quasi 3D flow modelling procedure presented by Kuznetsov et al. (2012); Perez et al. (2011); Twarakavi et al. (2008); Zhu et al. (2012) in which coupled unsaturated-saturated water flow models (i.e., 1D models-fully 3D models) were applied at the regional and the catchment scale. It also differs from the parallel modelling approach presented by Coumou et al. (2008) in which a 3D model was used to solve fluid flow in complex geologic media. In the present study, we simultaneously quantify the uncertainty of model parameters, i.e., hydraulic conductivity, of bottom boundary conditions and of various soil layer depths, and evaluate its effect on soil-water storage and water stress, as well as yield in a sandy grassland. Our approach will illustrate how combined prior information with different resolutions can be used in water flow modelling for managing irrigation more effectively and practically in precision farming. We thus simulated water flow on a large field with high resolution characteristics of input factors to i) evaluate the computational efficiency and uncertainty of this modelling approach/framework); and ii) evaluate different irrigation scenarios to find an optimized and cost-effective irrigation scheduling. The proposed modelling approach is evaluated by implementing different irrigation plans with different resolution allowing to show which resolution of input data is sufficient to optimize irrigation scheduling.

2. Material and methods

2.1. Study site description

The study site is located in an agricultural area at the border between Belgium and the Netherlands (with central coordinates 51°19′05″ N, 05°10′40″ E), characterized by a temperate maritime climate with mild winters and cool summers. During the study period 2011–2013, the farmer cultivated grass. The farm is almost flat (less than 1% sloping up from the North-West to the south-East) and runoff is not considered to be important. The major soil is a typical Podzol (Zcg-Zbg type, moderately drained sandy soils with a clear horizons, according to the Belgian soil classification) or Albic Podzols (Arenic) according to WRB (FAO, 2014) with distinct Ap and C horizons. Maximum grass root density was found at about 6 cm and decreased from 6 to the end of Ap horizon (based on field observations). Based on observations, the groundwater table ranged from 70 to 155 cm, and the Ap horizon thickness was between 30 and 50 cm at various locations across the field depending on the topography. The field is partly drained by parallel drainage pipes, connected to a ditch in the North-West border of the field, and which are placed at 10–20 m intervals and at around 90 cm below the soil surface (as measured in the ditch). Fig. 1 shows the layout of the field. A Reel Sprinkler Gun irrigation (type Bauer rainstar E55, Röhren-und Pumpenwerk BAUER Ges.m.b.H., Austria) was used on a 10.5 ha field to optimize crop growth in the sandy soil during dry periods in summer. The field was irrigated three times throughout each growing season (cumulative amounts in 2012: 64.5 mm and in 2013: 85.4 mm).

In Belgium, around early April the average daily evapotranspiration surpasses the average daily precipitation: a deficit can therefore accumulate from April onwards, (meteorological-atmospheric drought) (Van Passel et al., 2016; Zamani et al., 2015). After September, the precipitation deficit tends to decrease as evapotranspiration reduces and rainfall increases. The rainfall exceedance probability (%) for the experimental years (April–September, i.e., growing season which constitute the time period during which irrigation takes place) was calculated using RAINBOW software (Raes et al., 2006) with 31 years (1985–2015) of rainfall data from a nearby station (Eindhoven, The Netherlands) on which a square transformation was carried out to obtain a normal distribution. A probability of exceedance of 20% corresponds to a wet year and of 80% to a dry year. 2012 was a 'wet' year with a probability of exceedance of 5%, while 2013 was close to a 'dry' year with 72% probability of exceedance.

2.2. Model conceptualization

As discussed earlier, some assumptions are necessary in 1/2/3D modelling of water flow simulation in vadose zone. The following assumptions were made in this study; 1) only vertical flow in the vadose zone was considered; 2) the upper boundary conditions are uniform for all locations over the field; and 3) a constant head bottom boundary condition was assumed (with specified depth of groundwater for each location). The latter is justified for the field study site owing to the presence of the drainage system. In this study, the hydrological model was integrated with the crop growth model to simulate water flow, root water uptake and soil water status over the field.

2.2.1. Crop growth model

The crop growth model LINGRA-N (Wolf, 2012) was used to