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A Multi-Approach Framework to Couple Independent Models for Simulating the Interaction between Crop Growth and Unsaturated-Saturated Flow Processes

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Abstract: Land surface and groundwater table are two key hydrologic boundaries for the water transfer from atmosphere to aquifer. Their functioning is strongly affected by the water flow through the unsaturated zone. Quantification of soil-moisture processes is a prerequisite for accurate watershed-scale groundwater modelling. Moreover, soil-moisture processes are affected by vegetation and crop growth. In many cases, the unsaturated zone has been simplified or even neglected in groundwater modelling. Depending on the depth to groundwater, the unsaturated zone cannot be neglected in every case. In shallow groundwater, capillary rise can further play an important role. It can lead to an increase in ET, thus producing a feedback between crop growth and groundwater flow. In order to simulate all the processes involved, it is important to integrate them by coupling sub-modules for the relevant processes. There are various codes to simulate vegetation and crop growth, unsaturated and saturated zone flow simultaneously in an integrated manner. However, these solutions are not sufficiently flexible for all cases. Therefore, in this paper we integrated WOFOST, a crop growth and production model, with HYDRUS-1D, an unsaturated flow model, and with MODFLOW, a saturated flow model. The coupling was done using a combination of two different approaches, external coupling (through input/output data manipulation) and with code wrapping. We used OMS3 for wrapping WOFOST, and PYTHON to write scripts. The model was tested in a synthetic case where the importance of a coupled model was shown, especially in areas with shallow groundwater.

***Keywords**:* Coupling; Crop Growth; Unsaturated; Saturated; OMS3; PYTHON

1 INTRODUCTION

Water resources assessment has to be conducted in an integrated manner. To properly understand and plan water resources management it is necessary to perform modelling that includes the whole system taking into consideration the interactions and feedbacks between different processes. Integrated modelling should account for crop growth, hydrology, ecology and solute transport. Moreover, models should be able to manage different data sources as well as different types of analysis and algorithms. Although there are crop growth models integrated with hydrological models available, (e.g., SWAT-MODFLOW (Sophocleous et al., 1999), MIKESHE (DHI, 1998), WOFOST-SWAP (van Walsum, 2011)) they are typically constrained to the specific scales and purposes for which they have been developed. Moreover, some of these packages are not modular, which makes it difficult to connect them with other models or tools. Finally, some codes are proprietary and not open to the user. There is a demand for flexible and easy to use modelling frameworks that can integrate different modules and analysis tools. Such

framework should maintain modularity, reusability, and interoperability or compatibility of both science and auxiliary components. The system should be driven by problem objectives, scale of application, and data constraints.
One way to do integrated modelling is by coupling independent modules. By doing this, more flexibility is gained since the desired models are used and adapted to the specific needs. There are various ways to couple external models. The simplest one would be by using scripts, which can create the appropriate input files, execute the model and read the output files and transform them as input files for the next model. If the necessary variables are not written into input files or read from files it could be necessary to modify the source code in order to get the correct variable data needed in a file. The drawback of this way of integration is that writing and reading files is time consuming. Another option is to use specific software that can wrap the original programs, and by doing this give access to the desired parameters and data that are in the memory.
The objective of this paper is to integrate WOFOST with HYDRUS-1D and MODFLOW-2000 by using a combination of wrapping and scripts under OMS3 and PYTHON.

2 MODELS

The unsaturated zone plays a crucial role in understanding many aspects of hydrology and ecology, including infiltration, soil moisture storage, evaporation, plant water uptake, groundwater recharge, runoff, and erosion. Water flow in the unsaturated zone is influenced by the lower boundary condition which depends on the groundwater level as well as by water uptake by plants. Crop growth depends on soil moisture, which also depends on the lower boundary conditions, which is determined by the groundwater heads. Therefore, in order to simulate crop growth it is necessary to integrate crop growth, flow through the unsaturated zone and flow in saturated zone. Here, we coupled WOFOST, a crop growth model with HYDRUS-1D for flow in the unsaturated zone and MODFLOW, for simulating flow in the saturated zone; the three of them have been widely used and extensively tested.
By integrating WOFOST with HYDRUS-1D, crop production estimated with WOFOST can be improved by a more accurate estimation of the actual transpiration with the root water uptake method and a soil moisture profile computed with the Richards equation during crop growth. The soil moisture profile can be strongly affected by the lower boundary condition in the unsaturated soil column, which is controlled by the groundwater table calculated by MODFLOW.

2.1 WOFOST

WOFOST (WOrld FOod STudies) performs dynamic simulation of the phenological development of crops from emergence till maturity on the basis of crop genetic properties and environmental conditions. WOFOST v6.0 (Supuit et al, 1994) has been implemented in the European Commission Crop Growth Monitoring System to simulate and forecast the production of annual field crops all over Europe in real-time (EC, 2007).

2.2 HYDRUS-1D

HYDRUS-1D (Šimunek et al., 2008) is a hydrological model for the analysis of water flow and solute transport in variably saturated subsurface media. It solves Richards' equation for variably saturated soils. The water flow equation incorporates a sink term to account for water uptake by plant roots. The root water uptake and transpiration are calculated according to Feddes et al. (1978). The evaporation is calculated with the Penman-Monteith equation.

2.3 MODFLOW

MODFLOW is a well know 3D saturated flow model. It numerically solves the three-dimensional groundwater flow equation for a porous medium by using a finitedifference method. In our case we used the version MODFLOW-2000 (Harbaugh, et al., 2000)

3 COUPLING

There are different options to integrate external programs.

1) Modifying the original code in order to have the coupled model within the same executable file.
2) Another option can do without modifying the original code; models interact through input/output files. However, if the variables of interest are not included in the default input or output files, it is necessary to make some small modifications to the source codes. This method increases simulation time since writing/reading operations slow down the performance.
3) Wrapping the original code using specialized software like OMS3 (David et al., 2002), OpenMI (Gregersen, 2007) or PYTHON (www.python.org). By doing this, it is possible to have access to variables, which are stored in a memory common to all programs making simulation more computationally efficient.

3.1 Coupling procedure

We wrapped WOFOST into OMS3 and coupled it with HYDRUS-1D and MODFLOW. The interaction between WOFOST/HYDRUS-1D and MODFLOW was done through a script written in PYTHON, which is controlled by OMS3. The data transfer between WOFOST and HYDRUS was done following Li et al. (2011) and Zhou et al. (2012), and the integration between HYDRUS-1D and MODFLOW was done by following the boundary updating scheme proposed by Peña-Haro et al. (2012). In our case, the data transfer between the models can be summarized as follows (Figure 1):

1) WOFOST calculates crop growth, taking as inputs the crop parameters and meteorological data. Between the many outputs that WOFOST can generate two are of special importance, the Leaf Area Index (LAI) and the root depth. They are given to HYDRUS-1D as an input.
2) HYDRUS-1D calculates the potential evapotranspiration using the Penman-Monteith formula and the water uptake according to Feddes equation, which are given back to WOFOST. Therefore HYDRUS-1D needs as inputs the irrigation and precipitation, the daily net radiation, the daily maximum and minimum temperatures, the daily wind speed and the daily relative humidity. HYDRUS-1D also calculates the outflow from the unsaturated zone, which is an input to MODFLOW.
3) MODFLOW calculates groundwater heads taking HYDRUS-1D outflow as a recharge. The piezometric heads are then transformed to pressure heads and assigned as a lower boundary condition to HYDRUS-1D.

One of the advantages of externally coupling different models is that they can have different temporal and spatial resolution, which can enhance computational efficiency.

Time discretization

In HYDRUS-1D and MODFLOW variable time steps and stress periods can be assigned; however the structure of WOFOST only allows daily time steps. In our methodology it is possible to assign different time steps and stress periods in HYDRUS-1 and MOFLOW. Since groundwater processes are slower bigger stress periods can be assigned to MODFLOW in order to reduce simulation time.

Spatial discretization

MODFLOW domain is discretized into cells and the number of WOFOST/HYDRUS-1D profiles can be as large as the number of cells in one MODFLOW layer. However, MODFLOW domain can be divided into zones according to similarities on soil properties and depth to groundwater and only one WOFOST/HYDRUS1-D profile is assigned to each one of these zones.

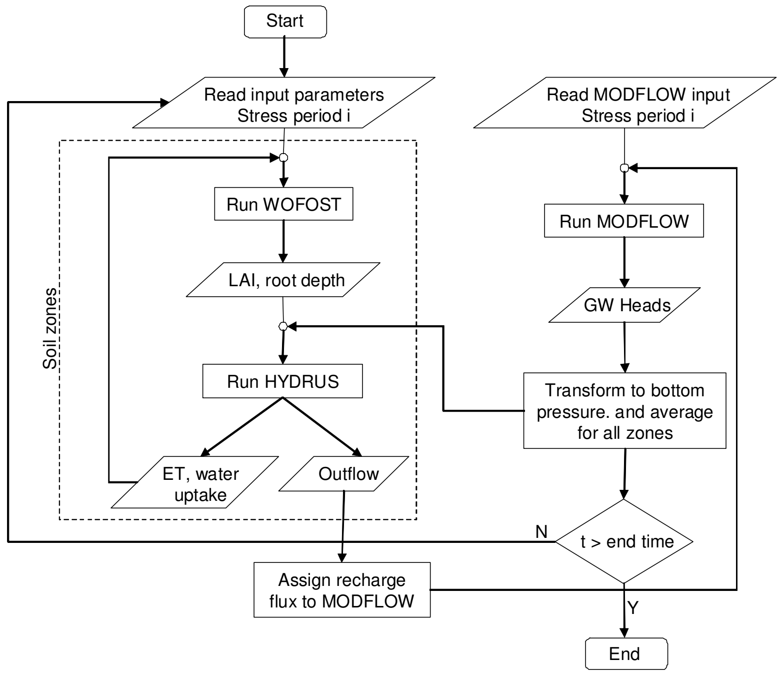

Figure 1 Coupling scheme

3.2 Model integration

Different procedures were followed to integrate the three models. First WOFOST was wrapped using OMS3 (see Zhang et al., 2012 from more details), which then was used to control HYDRUS-1D executions and a PYTHON script that controls MODFLOW execution.

There are several software platforms available that have been used to integrate models. Leavesley et al. (1996) reported the conversion of the Precipitation Runoff Modelling System (PRMS) to a Unix-based Modular Modelling System (MMS) for hydrologic modelling. Others are the European Open Modelling Interface (OpenMI) (Gregersen, 2007) and the Object Modelling System (OMS) (David et al., 2002). Despite of not having been conceived as an integrator for hydrological models, PYTHON is also very suitable to integrate models.

OMS (David et al., 2002) provides a component-based environmental modelling framework. The programming language interoperability is based on a DLL centric Java Native Access (JNA). OMS can be used to wrap FORTRAN and C/C++ codes into components which then can be assembled into a bigger modelling platform. PYTHON (www.python.org) is a programming language meant for integrating systems more effectively and easy to learn. It can also be considered as a general purpose scripting language. It has been widely used for the integration of hydrologic models with different types of application.

4 ILLUSTRATIVE EXAMPLE

The coupled model was tested in a hypothetical two-dimensional-vertical flow system, which has a height of 20 m and a length of 200 m (Figure 2). The saturated zone was discretized by cells of 5 m width. The initial hydraulic heads vary from 17 m on the left to 18 m on the right side of the domain. A prescribed hydraulic head of 17 m was set on the left side of the model. The aquifer has a saturated hydraulic conductivity of 2 m d^{-1} and a specific yield of S_y = 0.14. The unsaturated zone columns have a constant length of 3.5 m, and they are discretized into 351 nodes each. The HYDRUS-1D soil columns were homogeneous with the following soil properties: residual water content θ_r = 0.11; saturated water content, θ_r = 0.32; air-entry pressure head h_b = 0.168 m; and the pore size distribution index after Brooks-Corey λ = 1.7. A transient precipitation representative of an arid area was considered with a total annual precipitation of 32 mm. It was considered that maize is cultivated in the whole domain. The crop parameters correspond to the "maize_w41" available in the WOFOST database. An irrigation of 452 mm was applied. We considered synthetic parameters for the estimation of the root water uptake. The domain was divided into two zones, since the soil is the same in the whole domain, the MODFLOW cells were group only taking into consideration the depth to groundwater. The simulation time was 122 d from sowing to harvest. WOFOST has time steps of 1 d, which was also used as the stress period in HYDRUS1D and in MODFLOW. The computation time step in HYDRUS-1D was 10^{-5} d, in MODFLOW it was 0.1 d.

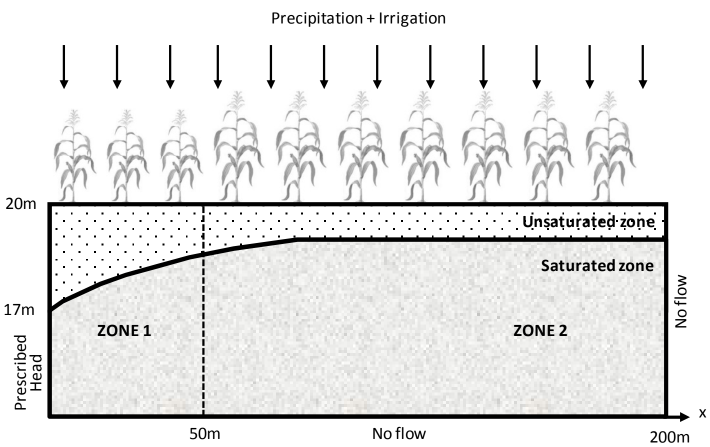

Figure 2 Illustrative 2D case

4.1 Results

The initial groundwater level is not the same for the whole domain since there is a prescribed head at the left of the domain; the heads are smaller in zone 1 than in zone 2. Its evolution in time is also different in the 2 zones, with zone 2 having a higher rise. The groundwater elevation can be transformed to pressure head which is the lower boundary condition in the unsaturated zone model (Figure 3). The groundwater level has an influence on the water uptake by the roots and therefore on the actual evapotranspiration. Since the groundwater level is different for both zones, the actual evapotranspiration is also different for both zones. The Leaf Area Index (LAI) shows the influence of the groundwater level on the crop development (Figure 4). In this case LAI is around 30% higher for zone 2 compared to zone 1. All these processes have also a feedback on the groundwater recharge (Figure 5), which as explained has a feedback on the crop growth.

To further show the influence of the groundwater table dynamics into the crop development, an additional simulation was performed were it was neglected the groundwater table dynamics (Figure 6). In this case, LAI development is much lower, around 40% less than the previous case. Therefore, a proper evaluation of the feedbacks between the different processes is very important in order to have a consistent simulation of the crop growth as well as the groundwater flow and unsaturated zone processes.

5 DISCUSSION AND CONCLUSIONS

In this paper we integrated a crop growth model (WOFOST) with an unsaturated zone model (HYDRUS-1D) and a saturated zone model (MODFLOW) following different coupling techniques. WOFOST was wrapped using OMS3, while

HYDRUS-1D was externally executed, but also controlled with OMS3. The data preparation for MODFLOW and its execution were done via a PYTHON script. This script was also controlled by OMS3; therefore the overall control was done with OMS3.

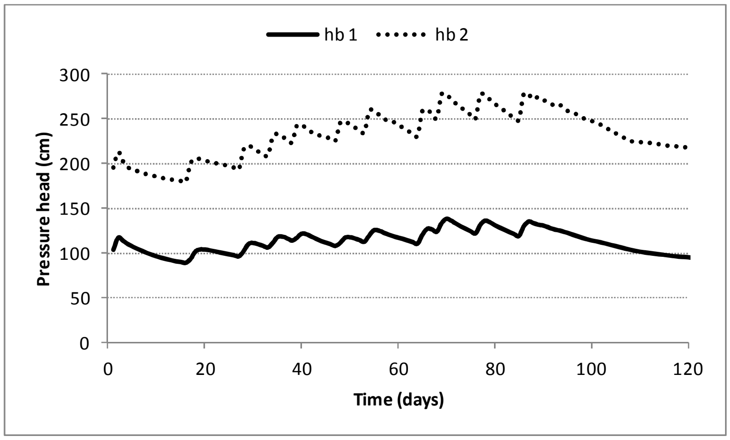

Figure 3 Pressure head evolution for both zones

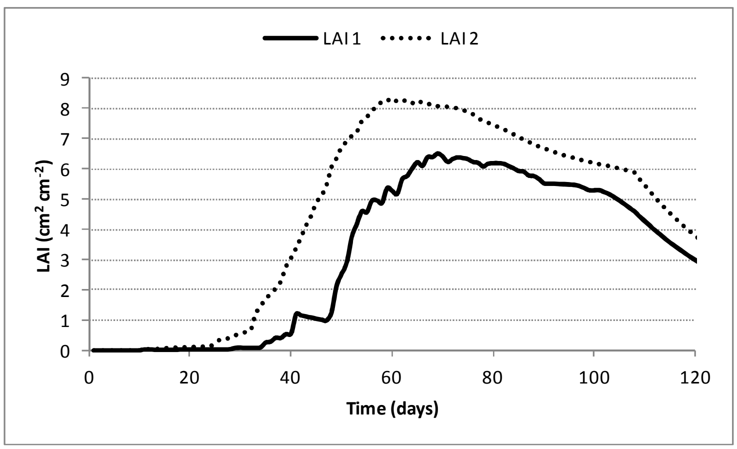

Figure 4 LAI evolution for both zones

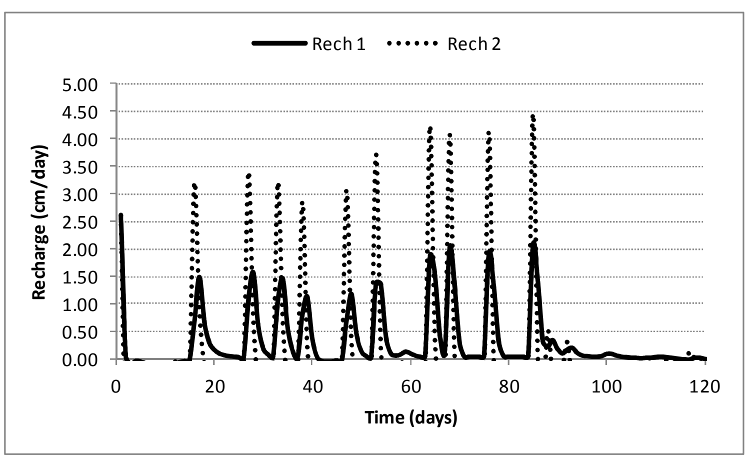

Figure 5 Recharge evolution for both zones

We tested the code in a synthetic case where the importance of considering all the processes involved and their feedbacks was shown. The LAI development depends on the amount of water available, which is influenced by the soil water content modelling. This in turn depends on the groundwater levels, which work as a lower boundary condition. In our illustrative case, where we have the same conditions in both zones, except for the groundwater level, which is controlled by a prescribed head, we can observe that the crop development is different between both zones. In our case study the groundwater level is shallow. Under these conditions there is an important influence of the groundwater level on the crop development. However, as the depth to groundwater gets larger, this influence is expected to diminish.

External coupling provides the possibility to extend the capabilities of well tested software without the need to have to write a new code. It has the advantage that integrated models can be developed relatively fast. In our coupling scheme we used different techniques, we wrapped WOFOST and we used scripts for controlling HYDRUS-1D and MODFLOW. The latter procedure is not computationally efficient, since reading/writing processes require large amounts of time. But on the other hand, it is much easier to integrate.

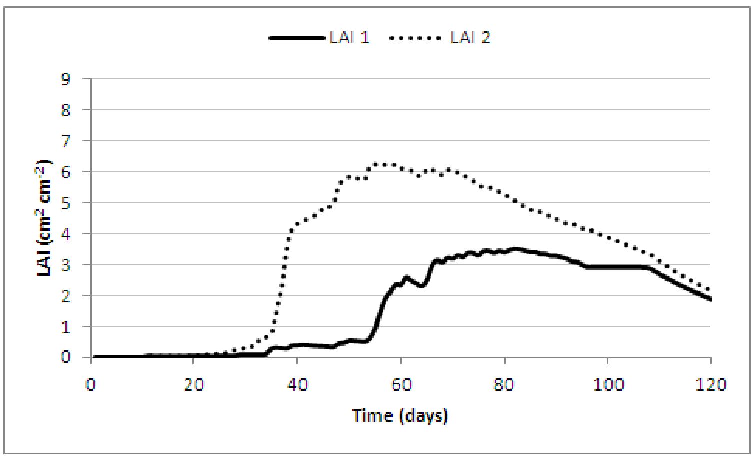

Figure 6 LAI evolution for both zones without considering the groundwater table dynamics.

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