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MODELLING THE INFLUENCE OF LANDSCAPE MANAGEMENT PRACTICES ON THE HYDROLOGY OF A SMALL AGRICULTURAL CATCHMENT

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ABSTRACT

A distributed hydrological model dedicated to the assessment of the influence of the influence of landscape management practices on the hydrology a small agricultural catchments is presented. It was built using an environmental modelling framework named LIQUID. The model consists of interconnected modules representing the major hydrological processes in subsurface-drained fields, non-drained fields, hedgerows and in the hydrographic network, and uses an irregular mesh that reproduces the real shapes of the different landscape features.

A model prototype was applied to the Fontaine du Theil experimental catchment (1.28 km²) in France. A six month simulation was performed in a winter period. The first results are physically consistent, in spite of limitations for simulating the seasonal variation of the discharge at the catchment outlet. Therefore we can consider that the modelling options that were chosen are promising.

Keywords: distributed hydrological model, modelling framework, landscape management practices

1. INTRODUCTION

In small agricultural watersheds, landscape management practices such as subsurface drainage, ditches or hedgerows affect considerably the different water pathways, with possible repercussions on river regimes or water quality. For example, tile drainage lowers the water table and reduces surface runoff, but is also responsible for fast water flow in the soil with a direct connection to the hydrographic network; ditches intercept surface and subsurface flows with also a fast connection to the river.

In order to assess the various influences of these landscape features at the catchment scale, appropriate modelling tools are required. In particular, these models should be able to represent explicitly all important landscape features, including their space locations and shapes, which may be particularly important for the hydrological response. The governing processes in each element should also be represented with an appropriate time discretization. The structure of the model must also be flexible enough to allow the addition/removal of some features, in order to evaluate their influence. However, most existing models are not well adapted to such representations: classically, distributed hydrological models are based on regular grid meshes and rely on one or two main governing equations and a unique time step.

The objective of this paper is to present a first prototype of an alternative modelling approach which represents hydrological systems at the closest of what they are in reality. It uses explicit representations that are defined as hydro-landscapes by Dehotin and Braud (2008) and that are, in our case, the different landscape features that can be found in North Western France watersheds (agricultural fields, tile-drained zones, hedgerows, ditches…).

2. MODEL PRESENTATION

2.1 The LIQUID modelling framework

The model was implemented using a framework for multi-scale hydrological modelling named LIQUID (Viallet et al., 2006). It allows the design, implementation and run of models as collections of temporally and spatially interconnected modules.

Within the framework, each module represents a specific hydrological process or a set of processes in a particular hydro-landscape. It has its own process conceptualization, and is associated to a GIS vector layer describing the hydro-landscape geometry. The latter can take any shape such as lines or polygons. The model mesh is extracted from these geometries so that the modules can be connected spatially.

Each module computes its own state variables and exchange variables thanks to an event-driven mechanism. It is also able to compute its own time step according to internal criteria, schedule its next execution in a common-shared calendar, and cancel/reschedule executions whenever required by changes in its inputs. This system allows a proper scheduling and synchronized data exchanges during a simulation. More details can be found in Branger (2007).

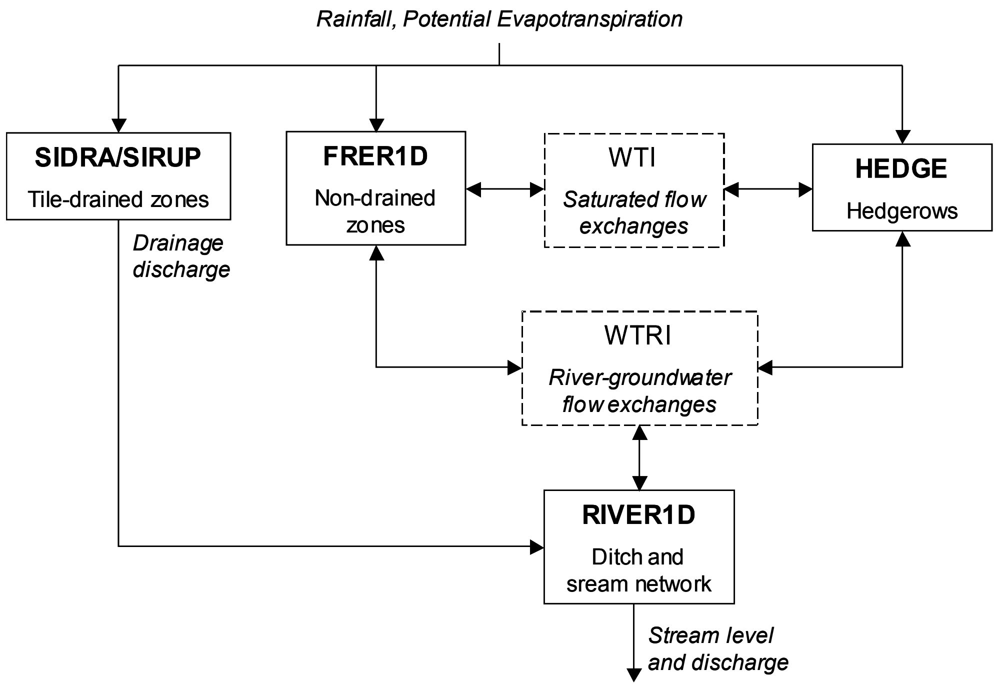

Figure 1: Constitutive elements and data flow diagram of the model.

2.2 Modules for hydrological processes in the different hydro-landscapes

The model involves four modules as represented in Figure 1. Each module is dedicated to the representation of the hydrological processes governing a particular hydro-landscape. All the modules have different process conceptualizations.

The SIDRA/SIRUP module allows to simulate the outputs of a tile-drained zone (ie drainage discharge and surface runoff). It is based on a spatial integration of the Boussinesq equation for the saturated zone, and a simplified capacity-based approach for the unsaturated zone as shown in Figure 2 (Branger et al., 2008).

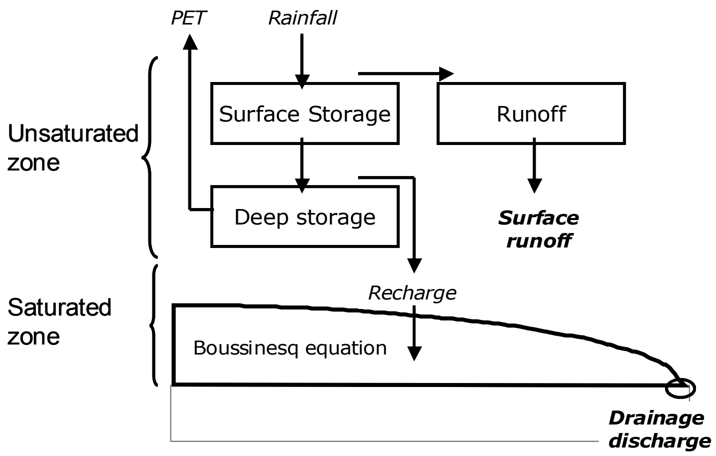

Figure 2: the SIDRA/SIRUP module for tile-drained zones.

The FRER1D module represents vertical infiltration and evapotranspiration in non-drained agricultural zones using a 1D resolution of the Richards equation (Ross, 2003). It is also adapted for receiving lateral flow in the saturated zone thanks to a source/sink term Q(z,t) (Eq.1). The soil properties are described using the Brooks and Corey (1964) soil coefficients (Eq.2).

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z} - 1 \right) \right] + Q(z,t) \quad (1)$$

$$\frac{\theta}{\theta_S} = \left(\frac{h}{h_e} \right)^{-\lambda} \; if \; h < h_e \; (else\, 1); \quad \frac{K}{K_S} = \left(\frac{\theta}{\theta_S} \right)^{\eta} \; if \; h < h_e \; (else\, 1) \quad (2)$$

where θ_S is the saturated water content, h_e the pressure and K_S the saturated hydraulic conductivity.

The HEDGE module is a conceptual module which allows to simulate the water table dynamics and evapotranspiration processes below hedgerows, following the approach that was developed by Viaud et al. (2005). It is also adapted for receiving lateral flow in the saturated zone (Figure 3).

At last, the RIVER1D module is a simplified flow routing module for the ditch and river network. It is based on the 1D kinematic wave approximation. Flow velocity is computed using the Manning relation. The river network is divided into several reaches with trapezoidal cross-sections that can receive lateral surface and subsurface flows.

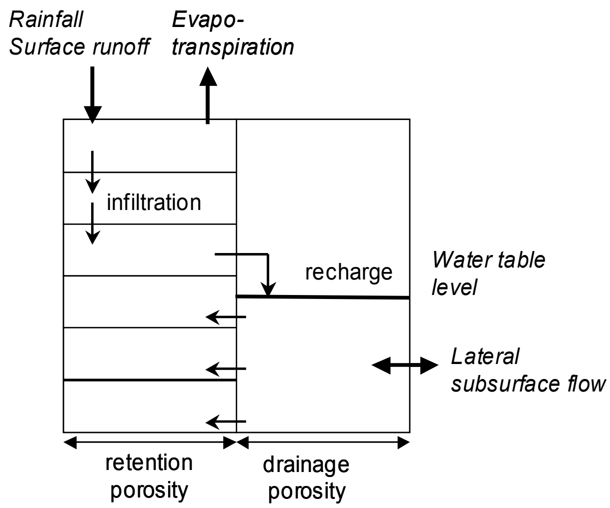

Figure 3: the HEDGE module for hedgerows. The soil is described by its porosity, which is conceptually divided into retention porosity (immobile water) and drainage porosity (mobile water).

2.3 Flow exchanges between the modules

In order to realize the spatial coupling between the different modules, flow exchange interfaces were added to the model (Figure 1). These interfaces allow to compute saturated lateral flow between the different hydro-landscapes in the catchment.

The saturated flow between agricultural fields and/or hedgerows is computed in the WTI (for water table interface) interfaces, using the Darcy law and a simplified parameterization.

$$Q_{1\to 2} = K \times A \times \frac{H_1 - H_2}{d_1 + d_2} \tag{3}$$

where K is the saturated hydraulic conductivity, A the contact area between the two fields, H_1 and H_2 the water table levels in the fields, d_1 and d_2 the distances between the fields and the interface.

The saturated flow between agricultural fields/ hedgerows and the river reaches is computed in the WTRI (for water table river interface) interfaces, using the Miles (1985) approach:

$$Q_{\to river} = K \times C_m \times \Delta H \text{ close to the river,} \tag{4}$$

where K is the saturated hydraulic conductivity, C_m the Miles coefficient (depending on the geometrical configuration and the water depth in the river reach) and ΔH the head loss of the water table close to the river;

$$Q_{\to river} = K \times (D_w - \Delta H) \frac{H_{river} + 0.5 \cdot (D_w + \Delta H)}{l} \text{ far from the river,} \tag{5}$$

where K is the saturated hydraulic conductivity, D_w the difference between the water table level and the level in the river, ΔH the head loss of the water table close to the river, H_{river} the water level in the river and l the distance between the river and the field.

3. MODEL APPLICATION AND RESULTS

3.1 Application case : the Fontaine du Theil experimental catchment

The first prototype of this model was applied to the Fontaine du Theil catchment (1.28 km²), which is located in Brittany, in North-Western France (Figure 4). The catchment was instrumented from 1998 to 2006 by Arvalis and UIPP for the assessment of non point source pesticide pollution. The hydrological monitoring consists of daily precipitation measurements in one rain gauge and discharge measurements at the catchment outlet at a 5 minutes time step. Geographical data (50 m digital elevation model, land use maps) are also available on the catchment.

The climate is oceanic with average annual precipitations of 800 mm regularly distributed along the year. The average annual discharge is 0.018 m^3/s. The soils are quite homogeneous, silty clayed, and lie on a shallow schistose bedrock. The catchment is dominated by agricultural activity (dairy farming and cereals). The agricultural fields are rather small (maximum 0.08 km²) and the landscape presents many specific management features such as tile-drained zones, and a dense hedgerow network (Figure 4).

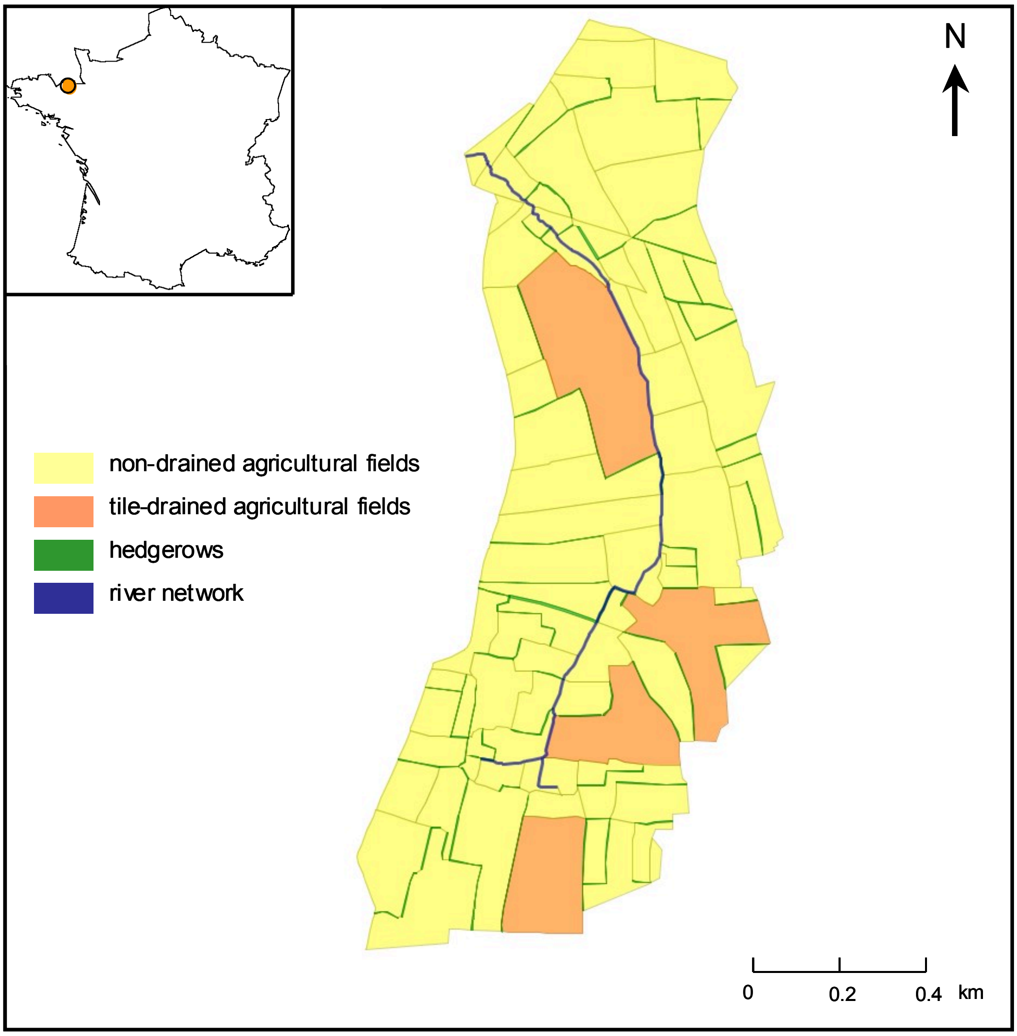

Figure 4: Location and main characteristics of the Fontaine du Theil experimental catchment in France.

3.2 Model parameterization

The mesh of the model follows exactly the limits of the agricultural fields (Figure 4). As a consequence, the model involves 4 tile-drained fields (SIDRA/SIRUP), 81 non drained fields (FRER1D) and 82 hedgerows (HEDGE). The modules parameters were set as simply as possible according to the available field data and literature data. In particular, uniform values were used for describing the soil properties in each module. The main parameter values are reported in Table 1.

A six-month simulation was performed during a winter period (October 1998-April 1999). The cumulative rainfall and potential evapotranspiration are respectively 539 mm and 149 mm for this period. The initial conditions were analogous for all the soil modules, with a water table level about 1.5 m below the soil surface. It corresponds roughly to the field observations at the end of the summer (although no measurements are available for the selected simulation period).

Table 1 Parameter sets for the different modules.

<table>
<tr><td rowspan="2">FRER1D</td><td>Sat. hydraulic conductivity (ms^{-1})</td><td>η (-)</td><td>h_e (m)</td><td>λ (-)</td><td>θ_s (-)</td></tr>
<tr><td>$1.2 \cdot 10^{-5}$</td><td>5.8</td><td>-0.3</td><td>0.8</td><td>0.46</td></tr>
<tr><td rowspan="2">SIDRA/SIRUP</td><td colspan="2">Sat. hydraulic conductivity (ms^{-1})</td><td colspan="3">Drainable porosity (-)</td></tr>
<tr><td colspan="2">$9.8 \cdot 10^{-6}$</td><td colspan="3">0.01</td></tr>
<tr><td rowspan="2">HEDGE</td><td colspan="2">Retention porosity (-)</td><td colspan="3">Drainage porosity (-)</td></tr>
<tr><td colspan="2">0.147</td><td colspan="3">0.147</td></tr>
<tr><td rowspan="2">RIVER1D</td><td colspan="5">Manning roughness ($m^{-1/3}s$)</td></tr>
<tr><td colspan="5">0.03</td></tr>
<tr><td rowspan="2">WTI/WTRI</td><td colspan="5">Sat. hydraulic conductivity (ms^{-1})</td></tr>
<tr><td colspan="5">$1.0 \cdot 10^{-4}$</td></tr>
</table>

3.3 Simulation results

The simulation results are presented in Figures 5, 6 and 7. The global behaviour of the model is not fully satisfactory, but yet encouraging at this stage of the model development (Figure 5). The model reproduces the base flow at the catchment outlet with a good order of magnitude (around 0.01 m^3/s) and reacts to the rainfall events with a correct timing (although the values of peak discharges are still approximative). The comparison of the simulated discharge at point A and at the catchment outlet also shows that the water supply of the river reaches by the surrounding fields is effective thanks to the flow exchange interfaces. However the model fails to reproduce the seasonal variation of the discharge.

First investigations showed that, although this seasonal variation is perceptible in the water table levels of the different agricultural fields (Figure 7), the computed lateral flows are not sensitive enough to the water table variations. Additional studies and tests are currently being undertaken to improve these aspects.

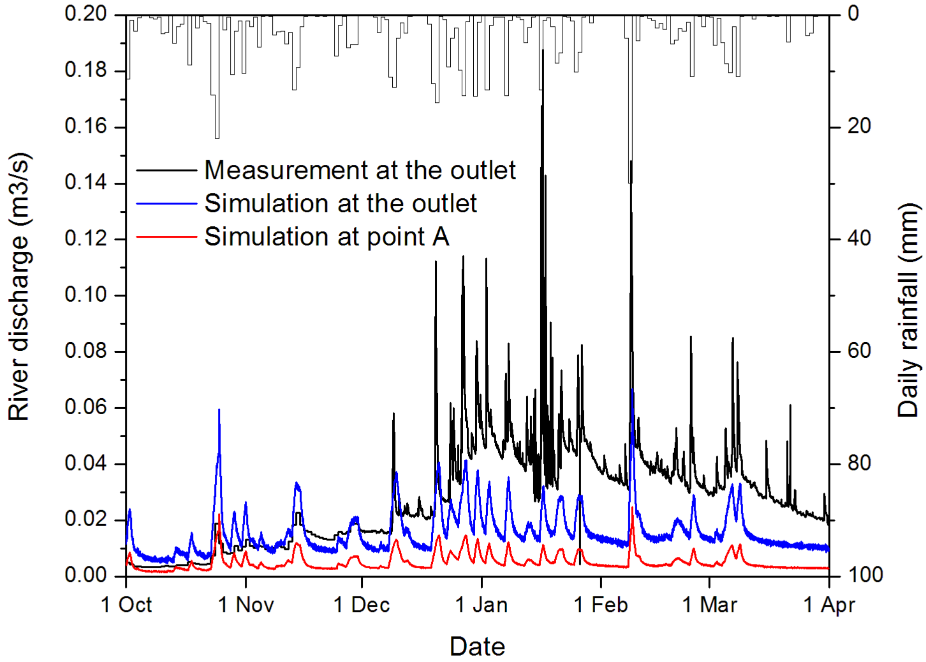

Figure 5: Simulated and measured river discharges. Point A is located in the upper part of the catchment (see Figure 7).

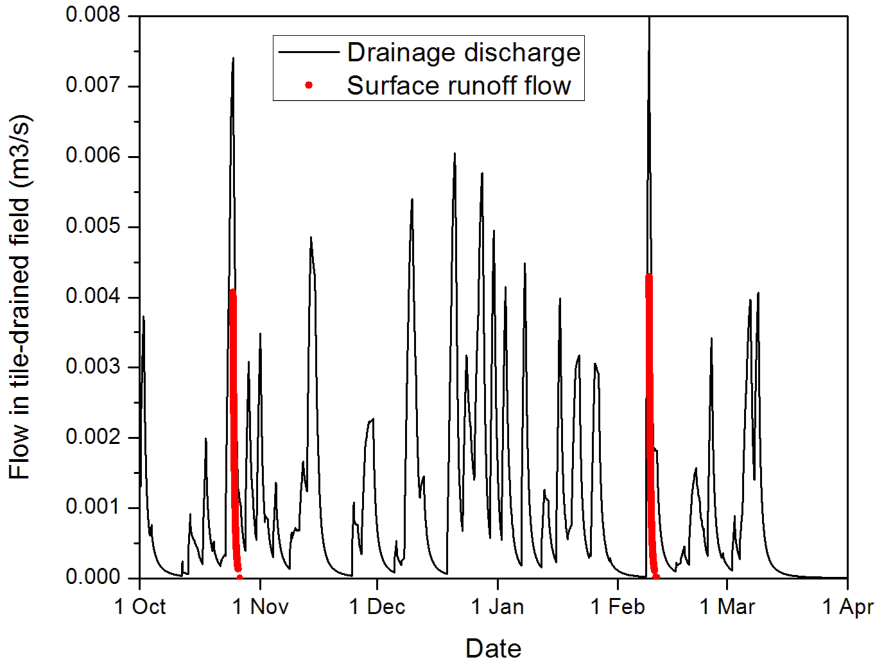

Figure 6: Simulation results for one of the tile-drained fields (see Figure 7 for the location of the field).

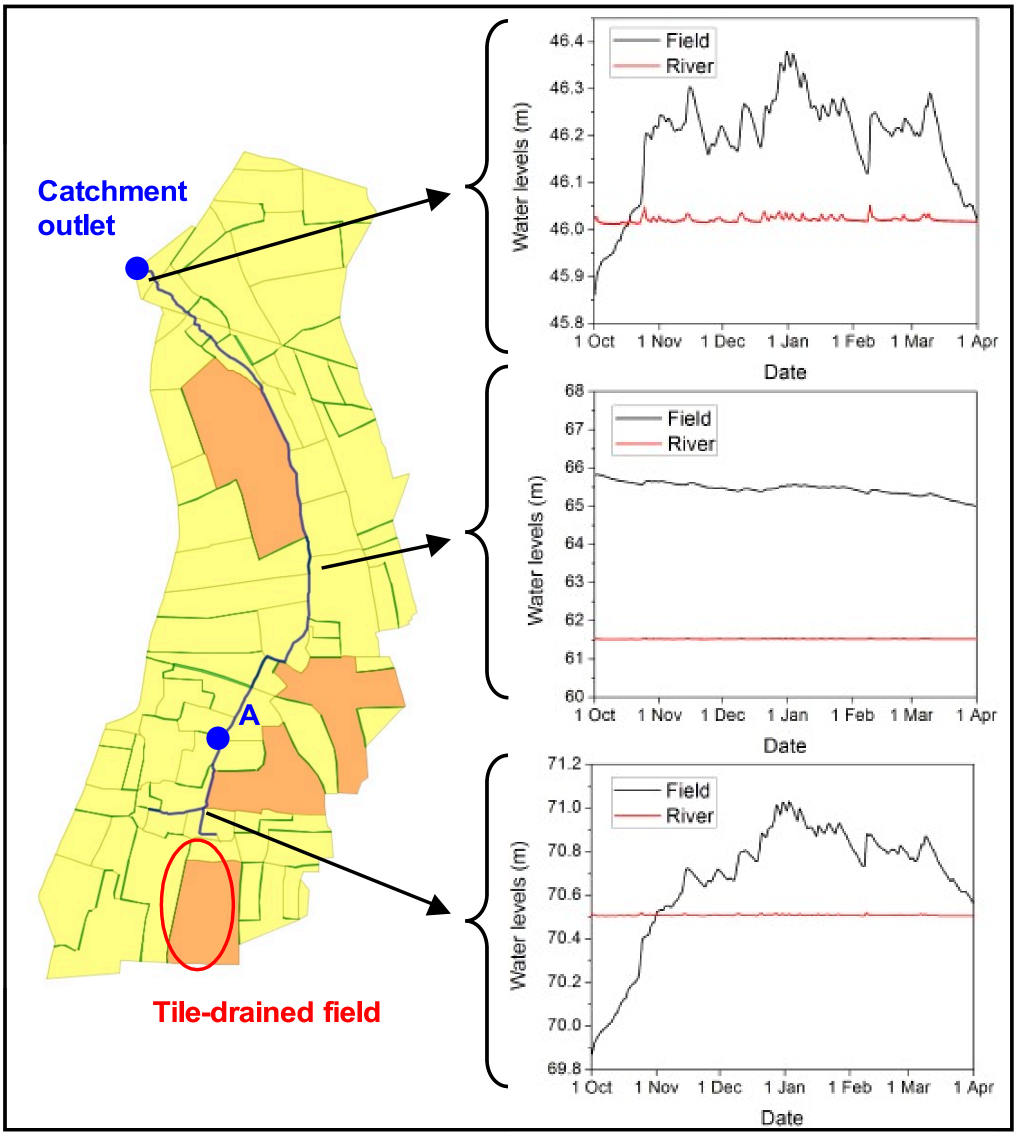

Figure 7: Simulated water levels for several agricultural fields and river reaches located at different places in the catchment.

The outputs of the tile-drained zones (Figure 6) show fast reactions of the drained water table to the rainfall events. The two surface runoff peaks correspond to the most intense events. These results are consistent with what can be observed for similar sites where measurements are available (Branger et al, 2008). The tile-drained zones are the main contributors to the catchment fast responses. The behaviour of the hedgerows (results not presented here) is also consistent with our expectations: in the winter, the hedges have no influence on the water table dynamics and mainly a role of water transfer.

4. CONCLUSIONS

This paper presents a model dedicated to the assessment of the influence of the influence of landscape management practices on the hydrology a small agricultural catchments. This model, built through the LIQUID modelling framework, involves four interconnected modules with different process conceptualizations for the relevant hydro-landscapes in such watersheds. The first simulations conducted with this model show a good general functioning. In particular, the interfaces allow to calculate adequately flow exchanges between the modules. The results are physically consistent, in spite of limitations for simulating the seasonal variation of the discharge at the catchment outlet.

The next step in the model tests and improvements will be the exploration of parameter sensitivities and the setup of calibration procedures in order to obtain a more accurate fit on the experimental data. Surface runoff will also be added in all the modules. This will allow to simulate different landscape management scenarios and to assess the influence of hedgerows and subsurface drainage on the hydrology of the Fontaine du Theil catchment.

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