Multiscale parameterization strategies for a spatially distributed hydrological model

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To predict the effects of land-use change on a heterogeneous catchments, one needs to use spatially distributed hydrological models. Although it was once sufficient to model only catchment outflow, growing concerns in pollution and water management require outputs at various points in a catchment, taking into account both surface and groundwater flow as these are the driving mechanisms of solute and sediment transport. These processes are very sensitive to the hydraulic properties of the soil surface and the channel network. The objective of the present study is to formulate and analyse a parameterisation strategy for the soil surface hydraulic properties used in infiltration-runoff models across scales on heterogeneous catchments. The methodology used herein is based on both experimental and modelling approaches at various scales. It consists first on identifying the main local features controlling infiltration and runoff at the local scale and suggesting a proper representation in the distributed model. The second step consists in the transfer of information from the local to the catchment scale through a spatial distribution scheme. The Roujan experimental catchment is used to illustrate our methodology. Three different scales are hence studied: the local scale of a single ring infiltration experiments (100 cm$^2$) used to identify soil hydrodynamic properties, the plot scale (1000 m$^2$) which is the management on farmed catchments and the small catchment scale (1 km$^2$) which represents the elementary scale of flood genesis.

First, soil hydrodynamic properties are identified at the local scale of the ring infiltrometer. Then these values are used in infiltration-runoff models to simulate hydrographs at the plot and the catchment scales. Various physically-based infiltration-runoff models and various strategies of spatialization of the soil hydraulic properties are compared. Multiscale calibration and validation approaches are used. Finally, a comparison of the values of the soil hydraulic conductivity obtained for the various scales and for the various approaches of calibration is undertaken in order to analyse the results function of the scale of use of the models. In the following sections, we present the main characteristics of the studied site, the hydrological models, the parameterisation procedures and describe the main results.

The study site

The study area is the farmed Roujan catchment (0.91 km$^2$) located in Southern France (Andrieux et al., 1993; Voltz et al., 1994). The catchment is mainly covered by vineyards and is divided into 237 plots. The major runoff events are usually caused by high-intensity short-duration storms, and are well representative of the hydrology in the Mediterranean zone. The main hydrological processes are runoff and infiltration at the field scale and the groundwater exchange through the ditch network at the catchment scale. The drainage network is formed by man-made ditches and generally follows agricultural field limits. Two main runoff control features are identified: soil surface crusts that limit infiltration and tillage operations that increase infiltration.

The basic instrumental design of the catchment consists of rain gauges, stream flow recorders, piezometers and tensio-neutronic sites. Experiments were undertaken at the local scale of a simple ring infiltration in order to identify soil hydrodynamic properties. Then, in an attempt to describe
spatial variability of runoff, discharge is measured at three gauging stations at the outlets of the catchment (0.91 km$^2$), a crusted plot (1200 m$^2$) and a tilled plot (3240 m$^2$). The sensors are read every minute. A network of piezometers has also been installed to measure the spatial variation of the water table at 10 minutes intervals.

**The hydrological models used across scales** At the local ring infiltrometer, the HYDRUS 2D two-dimensional vertical infiltration model (Šimunek and Van Genuchten, 1996) was used in inverse mode to estimate the soil hydrodynamic properties.

Moving up at the plot scale (the non-tilled and tilled plots), a rainfall-runoff model coupling a production function to a unit hydrograph transfer function, was used to simulate overland flow hydrographs. Three physically based production function models are compared: Richards-1D (Richards, 1931), Morel-Seytoux (Morel-Seytoux, 1978) and Philip (Philip, 1957) model. These models differ by their mathematical structure while input hydrologic data and the soil hydraulic properties used are the same.

Finally at the catchment scale, the MHYDAS distributed model (Moussa et al., 2002) was used. The model subdivides the basin into “hydrological units” taking into account the hydrological discontinuities of farmed catchments. Over each hydrological unit, MHYDAS simulates Hortonian mechanisms of overland flow using one of the three production functions studied above. Infiltrated water is assumed to flow vertically through an unsaturated layer from where it can flow to the groundwater. The flow exchange between the ditch network and the groundwater is calculated using a simple Darcian model. The unit hydrograph is used to route surface runoff at the scale of each hydrological unit, and the diffusive wave equation is used for flood routing through the ditch network. Evaporation is not represented since the purpose of the model is to simulate individual flood events. The model is most sensitive to the following parameters; the hydraulic conductivity at natural saturation $K_s$ of the hydrological units, the exchange coefficients between the reaches and the groundwater, and the average value of the Manning coefficient in the ditch network.

**The parameterisation procedure** The calibration process was subdivided in three main steps corresponding to each spatial scale.

First, the soil hydrodynamic properties were identified at the local scale using a simple ring infiltration experiments (14 cm $\varnothing$). Two separate single ring infiltration experiments were undertaken (Chahinian et al., 2004b). The first was performed on the undisturbed soil whereas the second was done after removal of the soil surface crust. HYDRUS 2D was then used, in an inverse modeling approach, to estimate first the soil hydraulic properties of the crust and the subsoil, and then the effective hydraulic properties of the soil represented as a single uniform layer. The results showed that the crust hydraulic conductivity (6 mm h$^{-1}$) is five times lower than that of the subsoil (29 mm h$^{-1}$) thus illustrating the limiting role the crust has on infiltration.

The second step concerns the plot scales. Two cases were distinguished, the crusted plot characterised by invariable surface features all round the year and the tilled plot characterised by variable surface features function of rain occurrence. Fourteen flood events were used for calibration and fourteen for validation:

- On the crusted plot, the use of the Richards-1D production function coupled to a transfer function shows that the representation of the soil as a single uniform layer gives similar results as the representation of the soil in a double layer (crust and the subsoil). The hydraulic conductivity at natural saturation ($K_s$) of the crust and subsoil considered as a homogeneous layer is 10 mm h$^{-1}$. When calibrating $K_s$ for Morel-Seytoux’s and Philip’s models, results show that the values range between 3 and 5 mm h$^{-1}$ depending on the calibration criteria (runoff volume, peakflow, or Nash and Sutcliffe criteria; Chahinian et al. (2004a)). The
calibrated values of $K_s$ are 50 to 70% lower than the values identified at the local infiltrometer scales. Finally, the comparison of the three models (Richards-1D, Morel-Seytoux and Philip) performance at the plot scale shows that all three models give accurate results and that the calibration of soil hydrodynamic characteristics in Morel-Seytoux’s model improves the quality of simulations and reduces the time of calculation in comparison to Richards’ model.

- On the tilled plot, the transient nature of soil surface properties needs to be taken into account. The calibration procedure consists first in calibrating the $K_s$ for each flood events, then in defining simple mathematical laws describing the evolution of $K_s$ in time. Results show that the value of $K_s$ decreases from a value of 25 mm h$^{-1}$ just after tillage to a threshold value around 4 mm h$^{-1}$ function of the total rainfall amount after tillage.

Finally at the catchment scale (1 km$^2$), three strategies for spatializing $K_s$ over the 237 plots were compared (Chahinian, 2004): (1) by calibrating a unique value of $K_s$ for all hydrological units, (2) by spatializing $K_s$ using the calibrated values at the plot scale and (3) by using values of $K_s$ obtained from rainfall simulations. For each strategy, the other parameters of the model (the exchange coefficients between the groundwater and the ditches and the value of the Manning coefficient) were calibrated using the measured hydrograph at the outlet of the whole catchment. Results show that the spatialized strategies give better results than the global one. The $K_s$ calibration for both crusted and tilled plots improves the quality of simulated hydrographs both on the eleven calibration events and on the six validation events. The calibrated $K_s$ values at the catchment scale are 20% higher than those calibrated at the plot scales. When calibrating each flood event individually, the $K_s$ values fluctuate between 0.5 to 12 mm h$^{-1}$ on the crusted plot and vary by $\sim$ 70% on the tilled plot.

**Conclusions** The aim of this study is to suggest and compare various parameterization strategies for runoff-infiltration models across scales on heterogeneous catchments. The studied scales are the local ring infiltrometer, the plot and the small catchment scales. The sensitivity analysis shows that the rainfall-runoff models, used at both the plot and the catchment scales, are very sensitive to the soil surface hydraulic conductivity. At both the local and the plot scale, results show that a single layer representation of the soil gives accurate results compared to a double layer. At the plot scale, the use of the Morel-Seytoux model gives comparable results to the Richards-1D but reduces the time of calculation. These results are similar on both tilled and crusted plots. However, on the crusted plot, soil hydrodynamic properties are constant all year round while on the tilled plot they vary in time function of rainfall amount and intensity. The calibrated $K_s$ values at the plot scale are 50% lower than those measured using the single infiltrometer ring and the calibrated values at the catchment scale are 20% higher than those calibrated at the plot scale. This multi-scale approach is well adapted to heterogeneous catchments characterized by different landuse types and runoff control mechanisms.
Bibliography


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