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Small Catchment Agricultural Management Using Decision Variables Defined at Catchment Scale and a Fuzzy Rule-Based System: A Mediterranean Vineyard Case Study

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Abstract Physically based hydrological models are increasingly used to simulate the impact of land use changes on water and mass transfers. The problems associated with this type of parameter-rich model from a water management perspective are related to the need for (1) a large number of local parameters instead of only a few catchment-scale decision variables and (2) the technical skills and computational expertise necessary to perform these models. This study aimed to show that it is possible to define a reduced number of decision variables and rules to synthesise numerical simulations carried out through a physically based model. The MHYDAS model was run on a Mediterranean vineyard catchment located in southern France (Roujan, Herault) for an actual, common rainfall event to calculate the runoff coefficient. The simulation results concerned 3,000 samples of contrasted scenarios. The scenarios were characterised by four catchment-scale decision variables related to agricultural practices: the proportion of the area of non agricultural land, the proportion of the area subjected to full chemical weeding practices (with the complement being mechanical weeding), the spatial arrangement of the practices based on the distance to the outlet and the initial soil moisture content. The simulation results were used to generate fuzzy linguistic rules to predict the runoff coefficient, as computed by the physical model from the decision variables. For a common end of spring rainfall event, simulations showed that the runoff coefficient was most heavily influenced by the initial soil moisture and the proportion of the area of full chemical weeding practices and the proportion of the area of other land uses and their spatial arrangement also played a role. The fuzzy rule-based model was able to reproduce

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the hydrological output with good accuracy ($R^2 = 0.97$). Sensitivity analysis to the rainfall magnitude showed that if the amount of rainfall was the key factor explaining the runoff coefficient absolute values, the structure of the rule base remained stable for rainfall events close to the one studied.

Keywords Surface runoff · Weeding practices · MHYDAS · Numerical experiment

1 Introduction

Agricultural activities generate many impacts on water bodies, modifying both water balance and water quality. Farm operations, such as tillage, influence surface roughness and, as a consequence, soil hydrological properties, including local surface runoff, infiltration and surface storage (Mwendera and Feyen 1993, 1994; Ahuja et al. 1998; Van Dijck 2000). By breaking up the soil surface crust, tillage can increase the infiltration capacity of a vineyard from 1 to 50 mm h^{-1} (Leonard and Andrieux 1998). Agricultural field patterns and associated ditch networks influence water transfer from fields to catchment outlets (Moussa et al. 2002; Assouline and Mualem 2006), by modifying water pathways and exchanges between the surface and groundwater (Hughes and Sami 1992). Under Mediterranean weather conditions, water quality is affected by the high leaching potential of herbicides (Albanis 1992; Sanchez-Camazano et al. 1995; Lennartz et al. 1997) and, in particular, by transport processes taking place in surface water at both field and catchment scales (Louchart et al. 2001).

Environmental requirements include therefore the implementation of safe agricultural practices for water resource preservation. A diagnostic evaluation may help growers to plan alternative practices and/or new spatial arrangements (Wu et al. 2001; Durga Rao and Satish Kumar 2004; Montero and Brasa 2005). This diagnostic involves different scales: agricultural production is planned at the field scale, while water resources are managed at the catchment one. Small catchments seem to be an appropriate decision-making scale for agricultural water management (Moreno-Mateos et al. 2010). They allow both the characterisation of the hydrological impacts due to cultivation practices and their spatial arrangements (Bormann et al. 1999) and a detailed description including tile drainages (Tiemeyer et al. 2007), ditch networks (Carluer and De Marsily 2004) or riparian areas (McKergow et al. 2003). In Mediterranean vineyard landscapes, because of the small size of fields (about 1 ha) and the high drainage density of artificial ditches, the areas of small catchments range from 1 to 10 km^2.

Existing physically based hydrological models have been used to accurately represent water, soil and pollutants transfers (i.e.: SWAT (Arnold et al. 1998), WEPP (Laflen et al. 1991) and MIKE-SHE (Graham and Butts 2006)). The MHYDAS model was developed to simulate water fluxes in intensively cultivated catchments and, particularly, to take into account spatial discontinuities, such as field limits and man-made hydrographic networks (Moussa et al. 2000, 2002). The model has been successfully tested in Mediterranean vineyard catchments to simulate the impacts of different weeding practices, their spatial arrangement, and ditch networks (Moussa et al. 2002; Chahinian et al. 2006b).

Physically based models have recently been used as “numerical experimentation” tools to explore potential hydrological impacts, which are difficult to assess by the way of field experiments (Holvoet et al. 2007). Weiler and McDonnell (2004, 2006) defined "virtual experiments as numerical experiments with a model driven by collective field intelligence" and argued that "these virtual experiments are essentially different from traditional numerical ones since the intent is to explore first-order controls in hillslope hydrology, where the experimentalist and model work to develop and analyse results collectively." This procedure allows simulating agricultural landscape modifications and assessing the resulting hydrological impacts.

However, physically based models remain difficult to implement as they require large amounts of exhaustive (environmental and hydrological) information and a high level expertise and technical skill (Pineros Garcet et al. 2006). Such models simulate water flows and quality either at the outlet (for lumped models) or within the catchment (for distributed models) based on climatological variables, landscape descriptions (soils, elevations, landcover) and cultivation practices. The direct use of these models does not allow to determine simple relationships between hydrological impacts and catchment scale decision variables, such as global soil moisture conditions, the spatial fragmentation of crop land or the distribution of the cultivation practices within the catchment. Therefore physically based models need to be simplified to become part of Decision Support Systems for agricultural consultants and water supply managers (Haberlandt et al. 2002; Pineros Garcet et al. 2006; Wohlfahrt et al. 2010). This can be done by the means of approximate reasoning using linguistic rules. Fuzzy logic is well known for its ability to handle linguistic concepts, such as High or Low (Zadeh 1975). These linguistic terms can then be used to build reasoning rules of the following form: "IF the percentage of cropland IS High, THEN the runoff coefficient IS Low". In the field of water management, Fuzzy Inference Systems have been used to simulate elementary processes (Bardossy 1996), river flows (Han et al. 2002; Akbari et al. 2009) and more complex processes on a large scale (Haberlandt et al. 2002).

This study aims to investigate whether it is possible to build a fuzzy rule based system that allows relating catchment-scale decision variables and hydrological impacts. The reference values for the impacts are those computed using a physically based model. The methodology includes the proposal of catchment-scale variables that are easy to use and relevant for agricultural decision making. The work is based upon numerical simulations of realistic scenarios over a representative Mediterranean vineyard catchment.

2 Materials and Method

2.1 The Study Area and Hydrological Issues

Due to its regionally representative position, the Roujan catchment (43°300′ N, 3°190′ E, 0.91 km^2) was selected to study the impacts of agricultural management, in particular, vineyard weeding practices, on water flows at the flood event scale.

This experimental catchment is monitored by the French National Institute for Agricultural Research (INRA) and is located in southern France, 60 km west of the city of Montpellier. The Mediterranean climate is characterised by high intensity, short duration storms (Andrieux et al. 1993). The annual rainfall ranges from 500 to 1,400 mm. The temporal distribution is bimodal, spring and autumn are the two major

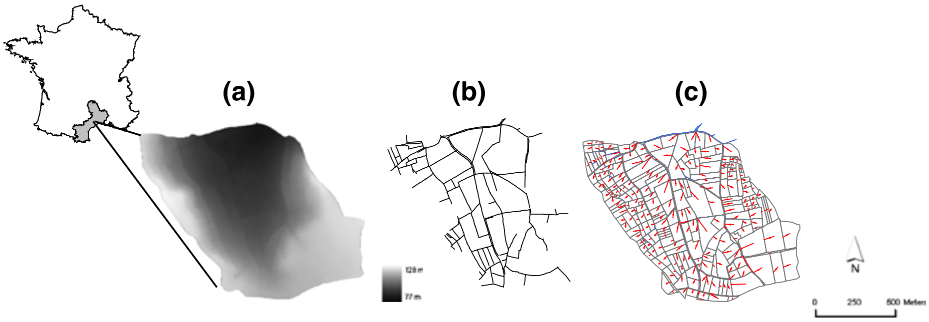


Fig. 1 The experimental Roujan catchment: location, elevations (**a**), ditches network (**b**), field boundaries and water pathways (**c**)

rainy periods. The mean annual temperature is 14°C, while the mean annual Penman evapotranspiration is 1,090 mm. The main soil texture ranges from silty loam to silty clay loam, and the predominant soil type is Calcisol (FAO 1998). The elevation ranges from 75 to 125 m. The hydrological network is composed of artificial ditches and follows agricultural field boundaries. The catchment is divided into 237 parcels with areas that vary between 320 and 22,427 m^2; it is mainly covered by vineyards. A catchment description is provided in Fig. 1.

Farming operations, particularly tillage, greatly influence local surface runoff, infiltration and surface storage by altering the soil hydraulic properties (Mwendera and Feyen 1994). Two main types of soil treatments are employed for weeding operations in the Roujan catchment (Biarnes and Colin 2006): either herbicides are applied over the whole field without any tillage (chemical weeding), or the soil is tilled between vine rows one to three times during the growing period between March and July and occasionally during autumn (mechanical weeding). Louchart et al. (2001) showed that two main processes are involved in water and herbicide transfers within the Roujan catchment. First, climate conditions and soil surface characteristics may generate surface runoff capable of quickly carrying away water

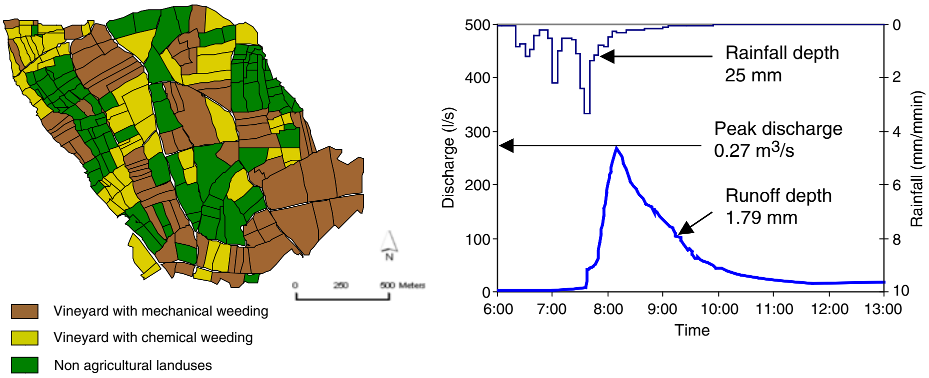


Fig. 2 The reference 1997 5th of June flood event: rainfall intensities discharges and associated land use map

and solute pollutants to catchment outlets. A second significant process is water and pesticide infiltration from ditches to the groundwater which is particularly common under semiarid climatic conditions.

Transfers were characterised at the flood event time scale because runoff, at the catchment outlet, is intermittent. A real flood event, which occurred on June 5th, 1997, was chosen for this investigation. In end of spring–beginning of summer, the infiltration is spatially heterogeneous due to the different weeding practices. This event can be considered as a median flood event with respect to either rainfall intensity or the total amount of rainfall (the maximum intensity over 60 min was 16 mm/h, with a total amount of 25 mm of rainfall, representing a semi-annual return period). The corresponding measured hyetograph, flood hydrograph and cultivation practice map are shown in Fig. 2.

2.2 The Hydrological Simulations with the MHYDAS Model

2.2.1 The MHYDAS Model

The MHYDAS model (French acronym for “distributed hydrological modelling for agrosystems”) is a physically based, rainfall-runoff catchment model. It has been used in cultivated catchments and has been thoroughly described by Moussa et al. (2000, 2002, 2003) and Tiemeyer et al. (2007). This model has been specifically enhanced to deal with the Mediterranean vineyard context. It considers a catchment as a series of interconnected surface units.

Over each unit, MHYDAS simulates the infiltration-runoff partition as Hortonian overland flow: the infiltration rate is calculated from a set of equations derived by Green and Ampt (1911) and Mein and Larson (1973), and adapted by Morel-Seytoux (1982). Comparing rainfall intensities and infiltration rates (depending on soil type and soil surface characteristics) allows calculation of the rainfall excess on each surface unit. The main parameter is the saturated hydraulic conductivity, and the initial conditions are related to the soil water content. Runoff is computed over each surface unit and routed to the hydrographic network (including via other surface units) according to a surface water pathway topology.

The network is considered as segmented linear units routing water to the catchment outlet. The routing method is the unit hydrograph using the Hayami approximation solution to the diffusive wave equation (Moussa 1996, 1997). Groundwater is considered as a compartment receiving infiltrated water from surface units. Water can also be exchanged between the hydrographical network and groundwater as a result of the difference in water levels using a Darcian form equation.

2.2.2 Parameterisation of the Roujan Catchment

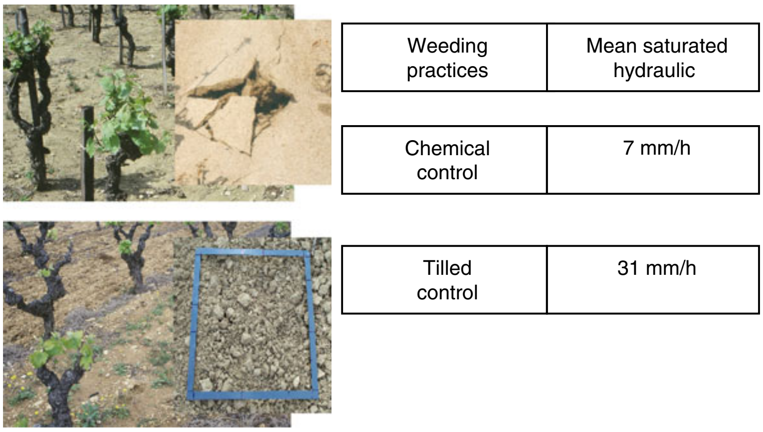
MHYDAS requires the spatial distribution of parameters on surface units (the agricultural fields), linear units (the reaches) and groundwater units. To avoid the calibration of parameters and the associated problem of equifinality (Beven and Binley 1992; Refsgaard and Knudsen 1996; Refsgaard 1997), a direct parameterisation strategy was used. Three kinds of parameters can be distinguished: those extracted from geographical data, those obtained from field observations and those determined from the analysis of hydrological data at the field scale (see Table 1).

Table 1 Parameters used for the MHYDAS model and associated parameterisation method

Parameters	Source of the information	Spatial organisation
Surface units: area, distance between units, slope Linear units: length, slope, distance between units Groundwater units: area Topology between all these units	Information layers: DEM, parcels limits, hydrographic network, groundwater limits	GIS routine
Surface units: residual and saturation water content, capillary succion Groundwater initial levels	Measured on field	Extrapolated considering soil types
Surface units: saturated hydraulic conductivity, initial soil moisture	Chahinian et al. (2006a, b); rainfall simulator measurements	Spatially distributed by simulation planning
Hydraulic parameters: celerity, diffusivity, roughness coefficients Exchange coefficients between hydrographic network and groundwater	Moussa et al. (2000, 2002, 2003), Chahinian et al. (2006a, b)	Mean value over the whole catchment
Groundwater initial levels	Measured on field	Extrapolated considering groundwater limits

Geometric characteristics, such as the area, the mean slope and the distance to another unit or to the reach for a given hydrological unit, as well as the length and the mean slope for a given reach, were automatically extracted using GIS procedures (Lagacherie et al. 2010). The following input data were used: a 2 m resolution Digital Elevation Model (DEM) derived from low altitude aerial photographs, the delineation of the 237 fields included in the catchment, the delineation of the 11 km reach network, and a simplified soil map.

The parameters measured or observed in the field were geometrical characteristics of the ditch network (Lagacherie et al. 2006), such as reach depth and width, Manning roughness, together with soil water properties and aquifer geometry. Soil properties, including the residual water content and the saturated water content, were calculated from field observations and considered as mean values over the whole catchment: 0.02 and 0.39 m^3/m^3, respectively. Initial water content at the soil surface was estimated from field measurements for each of the four geomorphological domains given by the soil map, depressions, glacis, terraces and plateaus (Hebrard et al. 2006). The groundwater level at the beginning of the flood event was also obtained from field measurements. The parameter to be calculated from hydrological data analysis at the field scale was the saturated hydraulic conductivity, Ks. Because Ks highly depends on tillage practices, hydrological units can be grouped into different classes according to weeding practices: nontilled or tilled fields, as shown in Fig. 3. Chahinian et al. (2005, 2006a) used the Morel-Seytoux model coupled to the Hayami unit hydrograph to simulate 28 flood hydrographs in a nontilled experimental field (1,200 m^2) in the Roujan catchment. Their Ks values are quite similar to the infiltration values



Weeding practices	Mean saturated hydraulic
Chemical control	7 mm/h
Tilled control	31 mm/h

Fig. 3 Dominant vineyard weeding practices and measured infiltration rate associated

measured on the same field, at a 1 m^2 scale by Leonard and Andrieux (1998). A similar approach was also applied (Chahinian et al. 2006b) in a tilled experimental field (3,200 m^2). These sets of parameters were used in MHYDAS to simulate either moderate flood events, 14 events with a mean Nash–Sutcliffe coefficient of 0.63 (Chahinian 2004), or extreme flood events inducing overbank flow, 12 events with a mean Nash–Sutcliffe coefficient of 0.68 (Ghesquiere 2008) in the Roujan catchment.

2.2.3 The Model's Output

Among the MHYDAS outputs, the runoff coefficient (RC, ratio of the runoff depth to the rainfall depth) was chosen to describe the simulated flood hydrograph for the outlet.

2.3 Catchment-Scale Decision Variables

Small catchment management requires systems that involve decision variables defined at the catchment scale. These variables have to influence the hydrological response; they also must be meaningful to catchment managers and easy to estimate, even in a rough way. The considered influential factors are: the types of cultivation practices and their scheduling with respect to a rainfall events, their respective areas over the catchment, their locations and, in particular, their hydrological distances to the outlet. The output variable representing the hydrological response is the runoff coefficient.

Local runoff processes are dependent on initial soil moisture conditions, such that the related variable (SoilMoist) is assumed to be the same over the whole catchment at a given date. Runoff also depends on the saturated hydraulic conductivity. This parameter is related to land use and weeding practices.

Three decision variables are then defined:

- NonAgri, the non agricultural percentage: the part of the catchment area occupied by forest and bushes;

Table 2 Catchment scale variables used as system input/output

Input variables	Output variables
SoilMoist—Initial soil moisture	RC—Runoff coefficient
NonAgri—Non-agricultural area percentage	Pd—Peak discharge
FullChem—Full coverage chemical weeding area percentage	
MechWeed—Mechanical weeding area percentage	
SpatArrang—Potential runoff in relation with the spatial arrangement of fields in the catchment	

- FullChem, the full coverage chemical weeding percentage: the part of the catchment area in which this practice is used;
- MechWeed, mechanical weeding percentage: similar definition to that of FullChem.

These variables are linked by the following relationship:

$$\text{NonAgri} + \text{FullChem} + \text{MechWeed} = 100 \tag{1}$$

Finally, the runoff coefficient is likely to be affected by the spatial arrangement of the weeding practices assuming that the closer the field to outlet, the higher its impact.

To build a corresponding variable, referred to as SpatArrang, the fields are ranked according to their hydrological distance to the outlet through simulations taking into account topology (field and reach position) and topography (elevation and related water path ways) of the site (Wohlfahrt et al. 2010). Three cases are considered for the SpatArrang variable. The first two are termed Favor and Disfavor. In these cases, most of the fields with chemical weeding practices are located close to (Favor) or far from (Disfavor) the outlet. In the last case, termed Neutral, the land cover and practices are randomly distributed over the catchment.

Thus, the system is made up of five input and two output variables, which are summarised in Table 2. They are all defined at the whole catchment level.

2.4 Database Building and Simulation Planning Steps

Various scenarios were developed by changing land cover and/or weeding practices while keeping the actual topology (number, size and location of parcels), hydrographical networks and groundwater conditions the same.

The four steps to build a scenario are summarised hereafter:

1st step: An initial soil moisture was randomly chosen and set for all of the fields. The three possible labels are the following:

- Dry: initial soil moisture corresponds to the measured residual soil humidity;
- Wet: this value corresponds to the saturated humidity;
- MedWet: an intermediate situation.

Table 3 Initial soil conditions (SoilMoist) and their respective soil humidity

SoilMoist	Moisture conditions		
	Dry	MedWet	Wet
Soil humidity (%)	0.05	0.15	0.3

Table 4 Normal distribution parameters used to determine the values of soil hydraulic conductivity according to the considered practices

	Practices					
	FullChem		MechWeed		NonAgri	
Normal distribution parameters	μ	σ	μ	σ	μ	σ
Ks (soil conductivity, 10^{-7} m s^{-1})	19	3	58	14	97	24

The numerical values are reported in Table 3.

2nd step: The non agricultural area percentage (NonAgri) was randomly determined in the range [0–40%]. These limits are common in southern France.

3rd step: The relative proportion of full coverage chemical weeding (FullChem) within the remaining catchment area was randomly assigned in the range [0–100%]. Once the FullChem and NonAgri variables were known, MechWeed could be determined according to Eq. 1.

4th step: Three land use spatial arrangement cases were simulated. For case 1, “Favor”, FullChem was randomly assigned to 80% of the parcels close to the outlet until the expected percentage of surfaces had been reached. The other land uses were randomly assigned to the remaining fields. For case 2, “Neutral”, FullChem, MechWeed and NonAgri were randomly assigned to all fields in the catchment. Case 3, “Disfavor”, is designed in a similar way of case 1; the difference is that FullChem was randomly assigned to the fields far from the outlet.

These four steps were run 1,000 times, thus yielding a database of 3,000 different distributed configurations for the catchment.

For each parcel, the soil saturated hydraulic conductivity parameter (Ks) was determined according to land cover and cultivation practices (Fig. 3). To take into account the potential variability encountered at the catchment scale, Ks values were randomly chosen within a normal distribution N(m,s). The mean (m) and standard deviation (s) values of the normal distributions, reported in Table 4, were deduced from rain simulator measurements.

2.5 Fuzzy Rule-Based System Design

Many techniques are available to generate fuzzy rules from data, but only a fraction of these actually produce interpretable systems (Guillaume 2001). A fuzzy decision tree induction algorithm was used in this study. A fuzzy decision tree is a fuzzy extension of classical decision trees (Breiman et al. 1984; Quinlan 1986). The tree generation step includes a ranking of the input variables such that the most significant ones in explaining the target variable are the first selected. The difference between fuzzy and classical decision trees stems from partial membership to fuzzy sets representing linguistic concepts. As a result, a sample may partially belong to several leaves, and the inferred value is the outcome of an aggregation process, meaning an interpolation for regression trees.

The open source software used, FisPro (Guillaume et al. 2002), requires input partitions to be defined prior to running the algorithm. This critical step is now detailed for each input variable.

As the three labels of SoilMoist (Dry, MedWet and Wet) do not overlap, the corresponding partition is crisp.

The three proportions, NonAgri, FullChem and MechWeed, are managed in the same way. These are continuous distributions to be partitioned into three linguistic labels: Low, Medium, and High. The fuzzy set parameters are derived using the k-means algorithm, as shown in Fig. 4. Because the sum of the three proportions is constant, it is expected for the algorithm to use only a subset of these variables.

Even the generation of the SpatArrang variable corresponds to one of the three distinct codes, Favor, Neutral or Disfavor, and it is advisable to be cautious to consider these labels as fuzzy. In the "Favor" case for example, full chemical weeding practices are assigned preferentially (and not systematically) to parcels close to the outlet. A Favor (DisFavor) case is considered to be Favor (DisFavor) with a 0.7 degree of membership and Neutral with a 0.3 degree. A Neutral configuration is considered to be Neutral with a 0.7 degree of membership and both Favor and DisFavor with a degree of 0.15 each.

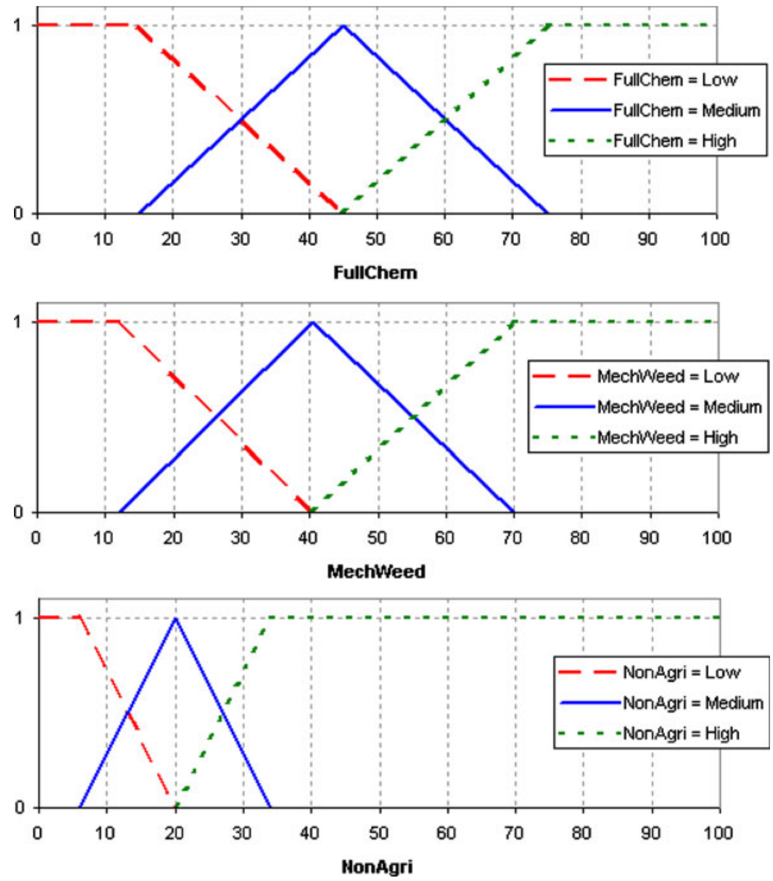


Fig. 4 Definition of the linguistic labels for FullChem, MechWeed and NonAgri variables

It has been shown that the surface runoff was a fast transport process that is mainly responsible for pollutant inputs into surface water, and in order to focus on its contribution to the catchment outlet, the chosen output variable was the runoff coefficient (RC). RC is managed as a scalar by the rule conclusion.

3 Results and Discussion

3.1 Simulation Results

The dependent variable is the runoff coefficient (RC), and the independent variables are the catchment scale decision variables (SoilMoist, NonAgri, FullChem, MechWeed and SpatArrang).

The overall statistical values of RC, computed from the 3,000 simulations, are given in Table 5. Both minimum values equal 0 because some simulations display no flow at the catchment outlet. The RC distribution is skewed: most scenarios lead to small RC values (90% of the simulated scenarios lead to RC values of less than 0.86%, and the other 10% lead to values between 0.86% and 4.6%).

In Fig. 5, the different subplots assist in investigating the relationship between RC and the dependent variables. Each column represents a given initial soil moisture. The three rows correspond to the three proportions of the land use, NonAgri, MechWeed and FullChem. Finally, the three spatial arrangement labels are represented using different symbols in each graph.

The initial soil moisture conditions are highly discriminant such that the drier the soil, the lower the runoff, with little overlap between the studied values. Under dry conditions, the simulated RC values are close to 0, whatever the other variables. Even with intermediate initial soil moisture conditions, the RC values remain very low and quite insensitive to changes in land use or spatial arrangement. The influence of the dependent variables becomes significant under wet conditions. In this case, the RC values range from 0% to 4.5%. These variations are not clearly correlated with either NonAgri or SpatArrang, even if NonAgri only varies between 0% and 40%.

The RC values tend to decrease as the area with mechanical weeding practices increases. The magnitude of this phenomenon increases with the initial soil moisture content. As expected, the reverse trend can be observed for the FullChem, with even less variability. The higher FullChem, the higher the RC. Moreover, SpatArrang seems to influence the RC: for a given FullChem, configurations with Favor exhibit a higher RC than those with Disfavor.

These simulation results suggest the possibility of designing a system to estimate the runoff coefficient from input variables characterising the whole catchment.

Table 5 Overall statistics of the hydrological indexes calculated by the simulation planning

	RC (%)	Pd (m^3/s)
Min	0.0	0.00
Max	4.3	0.20
Median	0.1	0.01
Mean	0.6	0.03
Standard deviation	1.0	0.04
Coeff. of variation	1.7	1.47

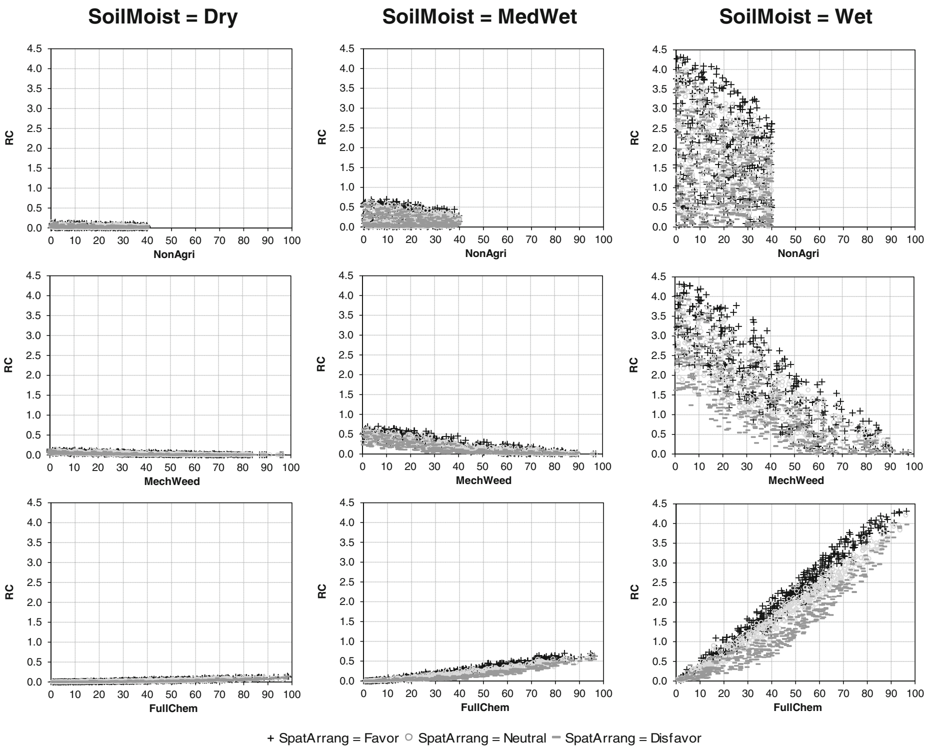


Fig. 5 Simulated runoff coefficient (RC) for different landuse percentage of surface (NonAgri, MechWeed, FullChem) setting apart different initial soil moisture conditions (SoilMoist) and landuse spatial arrangements (SpatArrang)

3.2 The Induced Regression Tree

The dataset was randomly split into two parts: 20% of the sample was used to generate the tree, while the remaining 80% was used to validate the system. Figure 6 shows the final pruned tree, in which the RC value is expressed as a percentage. The rule base derived from the tree was then used to validate the system via the subsample that was not introduced during the training phase. The result, plotted in Fig. 7, reveals that the system is able to manage the sample with satisfactory accuracy.

Each path from the root to a leaf corresponds to a rule. The rules are sorted in increasing order according to the runoff coefficient. They are summarised in Table 6. These proposed rules allow clearly synthesising the set of simulation results.

The rules can be expressed in natural language to facilitate their analysis. For example, rule 1, “if initial soil moisture is dry, then the runoff coefficient is low”; or rules 9 to 15, “if initial soil moisture is wet and the area percentage using chemical techniques is high, then the runoff coefficient is maximised”; or, as the more complex rule 6, “if initial soil moisture is wet and if the chemical weeding area ratio is moderate, then the runoff coefficient remains low, provided the spatial arrangement of fields with chemical weeding is unfavourable to catchment outlet flows”.

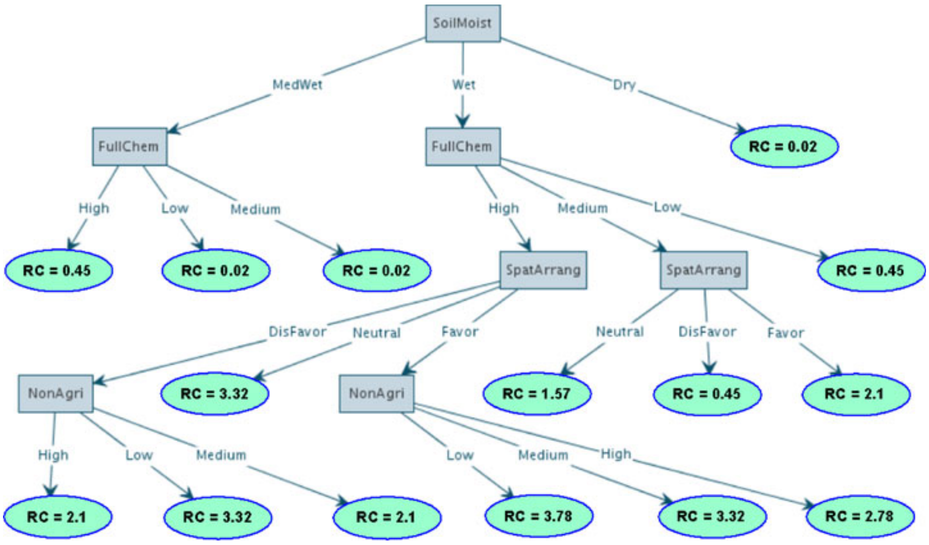


Fig. 6 The induced tree after pruning (RC values are given in %)

This table clearly shows that for a given common rainfall event, SoilMoist is the most influential variable, as the rules are also sorted according to this variable, such that the wetter the soil, the higher the runoff. Within each SoilMoist linguistic label, the rules are sorted according the FullChem one in the same order, such that the higher the proportional area of full chemical weeding practices, the higher the runoff coefficient. The next variable to appear in the induced tree is the spatial arrangement. The correlation of this variable with the runoff coefficient is as expected by hydrological experts; i.e., the runoff is higher in configurations in which the arrangement is supposed to favor it.

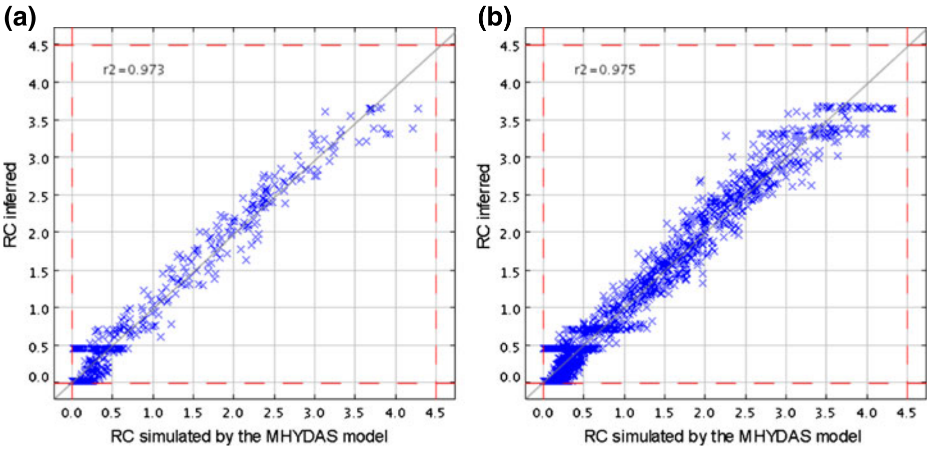


Fig. 7 System performance in calibration (**a**) and using a validation set (**b**)

Table 6 The rules induced from the 1997 June 5th rainfall event

Rule	SoilMoist	FullChem	Spat Arrang	NonAgri	RC (%)
1	Dry				0.023
2	MedWet	Low			0.023
3	MedWet	Medium			0.023
4	MedWet	High			0.45
5	Wet	Low			0.45
6	Wet	Medium	DisFavor		0.45
7	Wet	Medium	Random		1.565
8	Wet	Medium	Favor		2.099
9	Wet	High	DisFavor	High	2.099
10	Wet	High	DisFavor	Medium	2.099
11	Wet	High	DisFavor	Low	3.315
12	Wet	High	Random		3.315
13	Wet	High	Favor	High	3.315
14	Wet	High	Favor	Medium	3.784
15	Wet	High	Favor	Low	3.784

These rules are consistent with hydrological expertise: the initial soil moisture appears here as a predominant factor because the chosen rainfall event was relatively short (approximately three hours), and due to changing the saturated hydraulic conductivity of soil, the percentage of full coverage chemical weeding practices is in the second position.

To check the stability of the rule base, other numerical experiments were carried out with different rainfall intensities.

3.3 Rule Base Sensitivity to Rainfall Magnitude

To study the rule base sensitivity to the event magnitude, the rainfall intensity data have been modified using a scalar factor, with the hyetograph shape remaining the same. Intensities have been multiplied by 0.5 in the first case and by 1.5 in the second one. The whole procedure (MHYDAS simulations and tree generation) was carried out and resulted in to two new rule bases termed RB0.5 base and RB1.5 base.

Both rule bases differ by the absolute values of the RC. The higher the multiplicative coefficient of the rainfall intensities, the higher the RC was. The RC ranges were the following:

- 0% to 3.8% in the original rule base;
- 0% to 0.6% in the RB0.5 base;
- 0.2% to 6.3% in the RB1.5 base.

This confirms that the rainfall magnitude of the event is the most influential parameter of the runoff coefficient absolute values.

New rules, sorted according to the RC values, are shown in Tables 7 and 8 corresponding to the original ones. A comparison was made at the linguistic level without taking into account the absolute values of the RC, and instead using only its rank in the base. In the RB0.5 base, the NonAgri variable does not appear, and the difference between the three FullChem values when SoilMoist is MedWet is no longer required. This leads to a rule base simpler than the original one. The

Table 7 The rules base for lower rainfall intensities (RB0.5)

Rule	SoilMoist	FullChem	Spat Arrang	NonAgri	RC (%)	Original rule
1	Dry				0.0	1
2	MedWet				0.0	2, 3, 4
3	Wet	Low			0.005	5
4	Wet	Medium	DisFavor		0.012	6
5	Wet	Medium	Random		0.025	7
6	Wet	Medium	Favor		0.03	8
7	Wet	High	DisFavor		0.033	9, 10, 11
8	Wet	High	Random		0.049	12
9	Wet	High	Favor		0.059	13, 14, 15

correspondence between the two sets of rules is easy to find: rule 1 is identical in both bases; RB0.5 rule 2 includes rules 2, 3 and 4 of the original rule base; rule 3 is exactly the same as rule 5; rules 4, 5 and 6 in the RB0.5 base are numbered 6, 7, 8 in the original base; rule 7 in the RB0.5 base includes rules 9, 10 and 11; rule 8 is rule 12 in the original base; and finally, rule 9 corresponds to rules 13, 14 and 15.

Considering the RB1.5 base, one can observe approximately the same structure. SoilMoist and Fullchem remain the main important parameters, and most of the rules are unchanged and ranked in the same way for the three rainfall intensities considered. There is only one case where SoilMoist is equal to Dry in the original rule base, while in three cases in the RB1.5 base, it is designated relative to FullChem. This result means that when the rainfall intensity increases, the proportional area with full chemical practices become a significant factor, even if the initial soil moisture was dry. The result can be considered as a merged rule, as shown previously: the original rule 1 includes rules 1, 3 and 4 of the RB1.5 base. Rule 2 in the RB1.5 base inserts a MetWet label within the group of Dry ones. However, the rule cannot be interpreted as a structure problem, as the equivalent rule in the original base (rule 2) has the same RC value as the Dry one (rule 1). The same reasoning holds with respect to the inversion between original rules 4 and 5 and rules 7 and 6 of the RB1.5 base.

Table 8 The rules base for higher rainfall intensities (RB1.5)

Rule	SoilMoist	FullChem	NonAgri	Spat Arrang	RC (%)	Original rule
1	Dry	Low			0.18	1
2	MedWet	Low			0.48	2
3	Dry	Medium			0.68	1
4	Dry	High			1.28	1
5	MedWet	Medium			1.34	3
6	Wet	Low			1.66	5
7	MedWet	High			2.55	4
8	Wet	Medium			3.72	6, 7, 8
9	Wet	High	High	DisFavor	3.88	9
10	Wet	High	Medium	DisFavor	4.63	10
11	Wet	High	High	Random	4.69	12
12	Wet	High	Medium	Random	5.30	12
13	Wet	High	High	Favor	5.30	13
14	Wet	High	Medium	Favor	6.05	14
15	Wet	High	Low		6.30	11

The original rules 11 and 15 are combined into a single rule 15 in the RB1.5 base. When the rainfall intensity increases, the spatial arrangement becomes of second importance with respect to the proportional area of land use and the corresponding hydraulic conductivity.

Finally, the main structure of the three rule bases is similar, even if increasing rainfall magnitude induced some differences. These results indicate the robustness of the rule ranks, despite rainfall intensity changes of ±50% compared to the chosen rainfall event. This also shows the need to rebuild the rules when rainfall events change drastically.

3.4 Discussion

The initial complexity related to the direct use of the MHYDAS model (which is run using approximately 300 hydrological units, resulting in 3,000 parameters) has been considerably reduced. The fuzzy rules system is composed of 15 rules defined by at most four variables. Most of the input variables are simple to assess. The exception concerns the spatial arrangement, which is not straightforward to deduce from classical GIS layers, even when a field expert can say roughly whether a given practice is conducted near or far from the catchment outlet. Research is underway to improve the assessment of this variable using complex GIS algorithms or simpler rules (Wohlfahrt et al. 2010).

The rules used here are expressed in natural language and, consequently, become meaningful for interpretation by agricultural experts. Their a posteriori analysis is consistent with hydrological expertise. Such rules could be useful to a manager interested in partially reorganising agricultural activities within a catchment. The recommended modifications might, for instance, involve limiting the agricultural land use surface area, or changing the type of weeding practice employed. The manager could also take advantage of the key role played by the initial soil moisture in the system. Both the direct analysis of simulation results and the rules indicate that the initial soil moisture condition is the most influential factor controlling the runoff coefficient. To reduce its impact, tillage could be planned in relation to forecast rainfall. The rule system could also be used to compare various ungauged catchments with the aim of choosing one as a prior action zone, or to rank catchments according to their runoff coefficient for a given rainfall event.

In this study, we did not analyse the sediment and pollution losses at the outlet based on agricultural practices. Nevertheless, the larger the proportion of full chemical weeding practices, the higher the amount of sprayed pesticides and the higher the runoff. Therefore, it can be deduced that decreasing runoff through the use of mechanical weeding results in decreasing final mass losses.

Even though this approach seems to be general, the model itself has not been set up to perform a generic role: the induced rules depend on the agricultural, soil and climatic conditions, as well as on the simulation plan. Such decision rules can only be used in catchments similar to the one studied.

Particular attention must be given to the rainfall conditions used to establish the rule base. The driven sensitivity analysis showed that the rule base can be considered stable if rainfall characteristics remain similar, and it would not be used for a higher magnitude rainfall event. An actual, common rainfall event and its associated medium water flows were the focus of this investigation. It would provide an interesting perspective to perform this numerical experiment again using designed (synthetic) rainfall derived from statistical data and associated with a return period. This methodology could then be helpful to determine what the most influential rainfall characteristics are for a given catchment, which could provide insight related to extreme water flows and flooding events, in addition to dealing with other issues, such as flooding or erosion.

4 Conclusion

This report showed that it was possible to reproduce the output of a parameter-rich physical model using a fuzzy rule-based system with decision variables that characterise the general agricultural practices over a whole catchment.

The proposed approach is general because it is based on the following: (1) simulations of a model, (2) the definition of decision variables to characterise the different simulated scenarios, with these variables being easy to estimate and useful for decision making and (3) the inference of rules that associate the decision variables to the output of the physical model.

This approach was exemplified by the prediction of runoff from the decision variables. From an operational perspective, the value of this approach is the use of hydrological models to produce information that is understandable and useful to assist in catchment management.

Indeed, the extracted rules are specific to the considered catchment and may not be directly transposable to other situations. However, this study introduces new perspectives because it allows us to provide a description of a catchment using decision variables and rules that are meaningful for management purposes.

The definition of the decision variables remains a task requiring expertise and is strongly linked to the case study under consideration. This part of the approach may require methodological investigations to ensure the ability of these decision variables to properly describe some general characteristics of the catchment with parameters that are easy to measure. Finally, the estimation of other output variables important for watershed management can be considered within a similar approach, such as sediment and pollutant loads.

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