Hydrological modelling of flood events in a farmed mediterranean catchment

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ABSTRACT

The purposes of this study on the Roujan basin Southern France (1 km^2) are first to assess the hydrological behaviour of this Mediterranean agricultural basin, and then to assess the role of human impact on the basin hydrology especially the importance of the role of ditches network, terraces, tilled and untilled fields during flood events. For that, a spatially distributed hydrologic model linked to a Geographical Information System was developed. The model considers the catchment as a series of interconnected hydrologic units, chosen according to the catchment geomorphology in agricultural zone (limits of field parts, terraces and ditches network) characterized by topography, soil and vegetation cover properties. Detailed descriptions are provided for the main model procedures : hydrologically based subdivision of the catchment, computation of rainfall excess, conversion of rainfall excess into surface outflow, routing the channel inflow. Special attention is given in this model to the specific conditions of agricultural zone in Mediterranean climate. To analyse the human impact on hydrological processes, different scenarios were compared. Results show the importance of the role of ditches network and agricultural practices on the form of hydrograph, the lag time and the runoff volume during flood events.

1 INTRODUCTION

In agricultural Mediterranean catchments, hydrological processes are imposed by the spatial and temporal variability of the rainfall regime and the agricultural practices *(Voltz et al., 1997)*. In the agricultural domain, few catchments were installed and few hydrological models were developed to study the main hydrological processes. The agricultural basin of Roujan (1 km^2) Southern France was selected as representative of vineyard plain areas, strongly modified by human activity : ditches network, terraces, tilled and untilled fields.

Human impact such as agricultural terraces and the ditches network are expected to influence the basin response to rainfall *(Gallart et al., 1994)*. Spatially distributed models using physically realistic, process-based equations are one method of simulating the hydrologic behaviour of flow processes within catchments and predicting the human impact on hydrological processes *(Abbott et al., 1988; Fortin et al., 1995)*. In using hydrologic models, the context of their original purpose and development is often lost, so they are applied to situations beyond the scope of their capabilities *(Beven, 1989)*. In literature, very few hydrological models took into account the particularities of an agricultural Mediterranean catchment; this has led us to the development of a spatially distributed hydrological model able to represent the complex operation of a primarily man-made agrosystem.

A major consideration in the development of our flood event model was to take into account the role of ditches network during flood events in Mediterranean zone. The second consideration was the ability to assess the model simulations both against measured data and against qualitative field observations in order to ensure that the model is working well (or poorly) for the right reasons.

2 THE STUDY AREA

The elementary basin of Roujan is located in the Hérault valley Southern France, about 60 km west of Montpellier. It is almost entirely covered by the vineyards and has a surface area of 91 ha between 75 m and 125 m above sea level. Silty clay loam forms the top soil of the catchment. Four geomorphological and topographical domains were distinguished within the catchment area : central depression, glacis, terraces and plateau. Soils and geological outcrops differ markedly between these topographical domains. Terraces are usually about 1 m to 3 m high and 10 m to 50 m length, and have a man made containing wall of limestone *(Andrieux et al., 1993)*. The drainage network is formed by man made ditches and generally follows agricultural field limits.

The climate is Mediterranean with a mean annual precipitation of nearly 650 mm, showing a bimodal distribution with two rainfall peaks one in spring and the other in autumn. The precipitation is usually of high intensity and short duration. The mean annual temperature is about 14°C and the mean annual Penman evapotranspiration of 1090 mm.

The major runoff events are usually caused by high-intensity, short-duration storms, and the hydrologic response is dominated by Hortonian overland flow with subsurfaces processes being relatively unimportant. Rainfall intensity and the initial soil moisture state are the main factors affecting runoff production. The proportion of base flow is relatively small in each flood event.

The catchment is equipped with one meteorological station, four rain gauges, one streamflow recorder at the outlet of the catchment, two streamflow recorders at the outlet of fields (surface of 1300 m^2 and 3600 m^2), eight tensio-neutronic sites, seventeen piezometers and twenty monitoring sites of water geochemistry. These preliminary investigations were designed to identify the magnitude and the spatio-temporal variability of main hydrological processes. It also allowed to test the accuracy and the reliability of the equipments *(Voltz et al., 1994).*

3 MODEL DESCRIPTION

The model we developed consists of a series of interconnected hydrological units, each representing a specific portion of the area of the entire catchment. The interconnection between the units form a treelike structure which reflects the main drainage pattern and the topography of the basin. Units differ in the size, topographic features and soil properties of the area units represented by them and are connected to the channel network.

Over each unit the hydrological model incorporates Hortonian mechanism of surface runoff. Infiltrated water is assumed to flow vertically through an unsaturated layer from where it can flow downslope. The infiltration rate and volume as well as the rainfall excess are computed for each element using a relation based on an equivalence between the Green and Ampt and Horton capacity equations. The diffusive wave scheme is used for routing discharge through the ditches network. Evaporation is not represented since the purpose of the model is to simulate individual events.

Each unit in the model is composed of a number of elements that transform the unit's inputs into a single output in the form of a unit outflow hydrograph. This outflow hydrograph is the sum of the surface outflow hydrograph and the channel output hydrograph. The program starts with the upstream exterior units, and proceeds to the downstream units. The computation ends in the most downstream unit having its outlet at the outlet of the catchment.

The first step was to develop a set of computer programs that generate a network interconnected elements on a surface defined from Digital Elevation Models (DEMs) and then to subdivide the catchment into hydrological units *(Lagacherie et al., 1996)*. DEMs were derived from different data layers obtained from low altitude aerial photographs. Then, we used the ARC/INFO command *createtin (ESRI, 1992)* to merge the different layers in Triangular Irregular Networks (TIN). Gridded DEMs were computed by linear interpolation in triangle facets. The grid size of the DEMs was fixed at 2 m to avoid losses of DEM quality because of the grid resolution.

In this application, the hydrological units were defined as subcatchments. Subcatcments were delineated using the ARC/INFO GRID procedures. The ditches network was registered in the field and converted into an ARC/INFO line coverage. DEMs was combined with the ditches network coverage to build a flow direction grid that takes into account both the directions of flow given by the topography and the directions of flow imposed by the man-made ditches. Finally, the subcatchments of each node of the ditches network were delineated using the GRID function *watershed*. Figure 1 shows the ditches network and Figure 2 the subcatchments we obtained using the procedure described before.

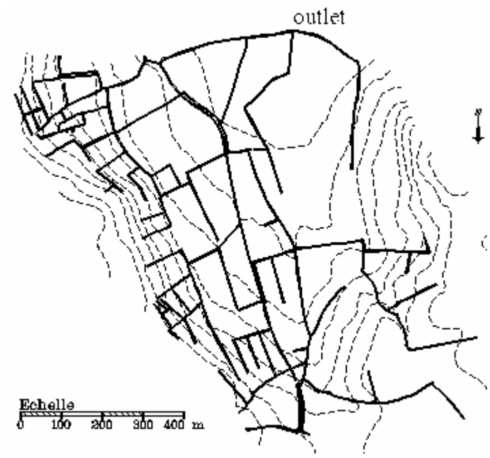

Figure 1 : The ditches network of the Roujan catchment.

The ditches network was divided into reaches corresponding to the part of the channel between two nodes. Each reach of the ditches network is characterised by geometric properties either derived from DEM (length, slope or elevation range) or measured on field (cross sectional area of the flow). Each subcatchment has physiographic characteristics of area, elevation range, mainstream length and mean slope, and is connected to a reach of the channel network.

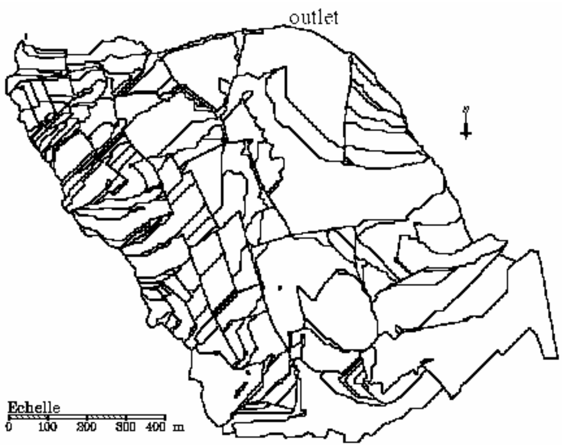

Figure 2: Subdivision into hydrological units (here subcatchments).

4 The model hydrological components

4.1 Determination of infiltration rate and effective rainfall

Because of its physical basis and good previous performance, we have adopted the pounding time formula proposed by *Morel-Seytoux (1982)*. Before pounding, infiltration rate equals precipitation rate and excess rainfall is equal to zero. After pounding, and while a pounded condition lasts, infiltration rate equals capacity infiltration rate and excess rainfall equals rainfall rate minus capacity infiltration rate. Pounding time occurs at the saturation of the soil surface and acts as a threshold determining which physical process should be considered to describe infiltration and is defined as

$$t_p = t_0 + \frac{1}{r_j}\left(\frac{S_f}{r_j^* - 1} - W_{j-1}\right) \tag{1}$$

where t_p is the time of pounding, t_0 is the time at the beginning of the current time step, r_j is the rainfall rate during the current time step, S_f is the storage-suction factor, r_j^* is the normalised rainfall rate and W_{j-1} is the cumulative infiltration depth since the beginning of the current continuous rainfall up to time t_0. The normalised rainfall rate in eqn (1) is defined as

$$r_j^* = \frac{r_j}{K_s} \tag{2}$$

where r is the rainfall rate and K_s is the hydraulic conductivity at natural saturation. The storage-suction factor is a composite factor affecting pounding and the infiltration process. Its value can be computed as

$$S_f = (\theta_s - \theta_i).H_c(\theta_i) \tag{3}$$

where θ_s is water content at natural saturation, θ_i is mean initial water content in an upper soil layer and $H_c(\theta_i)$ is the effective capillary drive, a quantity which only slightly depends upon the initial water content and can be estimated by the formula *(Morel-Seytoux, 1982)*

$$H_c(\theta_i) = \left[1 - \left(\frac{\theta_i - \theta_r}{\theta_s - \theta_r}\right)^6\right].H_c \tag{4}$$

for $\theta_i \geq \theta_r$. In this equation, H_c is the maximum value of $H_c(\theta_i)$ which is attained for $\theta_i = \theta_r$ with θ_r being the residual water content, a water content below which water is no longer mobile in liquid form.

During rainfall periods the pounding time is computed for each subsection of the catchment. Pounding may occur in different units during different time steps. In this way the area contributing to surface runoff may change in time, expanding or contracting. The capacity cumulative infiltration depth is computed by the equation

$$\frac{K_s}{\beta}(t_v - t_p) = W_v - W_p - \left[S_f + W_p\left(1 - \frac{1}{\beta}\right)\right] Ln\left(\frac{S_f + W_v}{S_f + W_p}\right) \tag{5}$$

In this equation K_s is the hydraulic conductivity at natural saturation, β is a viscous correction factor (between 1 and 1.7), t_v is time at the end of current time step, t_p is pounding time, W_v is cumulative infiltration depth at the end of current time step, W_p is the cumulative infiltration depth at the time of pounding, S_f is the storage-suction factor defined by eqn (3). At each time step, the effective rainfall which participate to surface runoff is calculated as the difference between total rainfall and infiltration.

4.2 Conversion of effective rainfall to surface runoff

The rainfall excess function for each cell is converted to a surface runoff hydrograph by routing it to the proper outlet of the cell, as a two-parameter Hayami response function *(Moussa and Bocquillon, 1996)*.

$$Q(t) = \frac{L}{2(\pi.D)^{1/2}}.\exp^{\frac{C.L}{2.D}} \int_0^t Re(t-\tau).\frac{\exp^{-\frac{C.L}{4.D}\left(\frac{L}{C.\tau}+\frac{C.\tau}{L}\right)}}{\tau^{3/2}} d\tau \qquad (6)$$

where Re is excessive rainfall, L is the length from the centre of gravity of each hydrologic unit to its outlet, C the celerity and D the diffusivity. C and D are two parameters function of the discharge Q and depend only on the unit topography (slope, shape and roughness).

4.3 Routing the channel inflow

The dynamic modelling of a one-dimensional unsteady flow in open channels generally uses the diffusive wave equation obtained by neglecting the acceleration terms in the momentum balance equation in the Saint-Venant system

$$\frac{\partial Q}{\partial t} = -C\frac{\partial Q}{\partial x} + D\frac{\partial^2 Q}{\partial x^2} \qquad (7)$$

where C and D are non-linear functions of the discharge Q and are known as celerity and diffusivity, respectively. For this problem the boundary conditions are Q(x,0) and the upstream inflow Q(0,t).

The runoff from each subcatchment constitutes lateral inflow into each reach. For each reach, hydrographs are added at the upstream then routed through the channel network to the downstream outlet to give the full hydrograph. The complete algorithm for solving the diffusive wave equation using the Crank-Nicholson approximation was presented and discussed by *Moussa and Bocquillon (1996)*. The celerity C and diffusivity D are taken as functions of the discharge Q using the Manning formula with

$$V = \frac{1}{n}\sqrt{i}R^{2/3} \qquad R = \frac{B.z}{B+2z} \quad \text{and} \quad A = B.z \qquad (8)$$

where V is the mean velocity, R the hydraulic radius, i the slope, n the coefficient of roughness, z the mean flow depth of a rectangular section, B the cross-sectional width and A the cross-sectional area of the flow. The two relations C(z) and D(z) used in Equations (6) and (7) are

$$Q = V.B.z \qquad C = \frac{dQ}{dA} = \left[\frac{5}{3} - \frac{4}{3}\frac{z}{B+2.z}\right]V \qquad D = \frac{Q}{2.i.B} \qquad (9)$$

Each reach of the channel network has three characteristics i, B and n. For each value of z, we calculated Q, C and D. So each reach is characterised by two relations C(Q) and D(Q). Then the surface runoff discharge simulated at the outlet of each unit is routed through the channel network. The total contribution of surface runoff of the whole catchment corresponds to the simulated hydrograph simulate at the catchment outlet node.

4.4 The baseflow

Since the proportion of base flow is relatively small in each flood event, an exponential model with one parameter α was used. The groundwater aquifer is represented by a reservoir; let z be the level of this reservoir. The baseflow Q_b is given by :

$$Q_b = \alpha z \qquad (10)$$

At the outlet of the basin, the simulated discharge is given by the sum of the surface runoff and the baseflow.

5 APPLICATIONS

Forty rainfall-runoff events were considered between 1992 and 1996. To make the problem simple, rainfall-runoff events in which the rainfall is nearly uniformly distributed over the catchment were chosen. The spatial distribution of rainfall was estimated by the Thiessen method. Ten events were selected for calibration and ten for validation.

The Manning roughness coefficient n was taken constant for all reaches (n=0.082), the storage-suction factor S_f=0. After calibration of the parameters (C, D and α), we obtain a mean values of the celerity C=0.145 $m.s^{-1}$, diffusivity D=6.5 $m^2.s^{-1}$ and the parameter α=1.35e-6/s. Two sets of values for the hydraulic conductivity at natural saturation (Ks) were considered for tilled (Ks=2.23 mm/h) and untilled units (Ks=8.91mm/h).

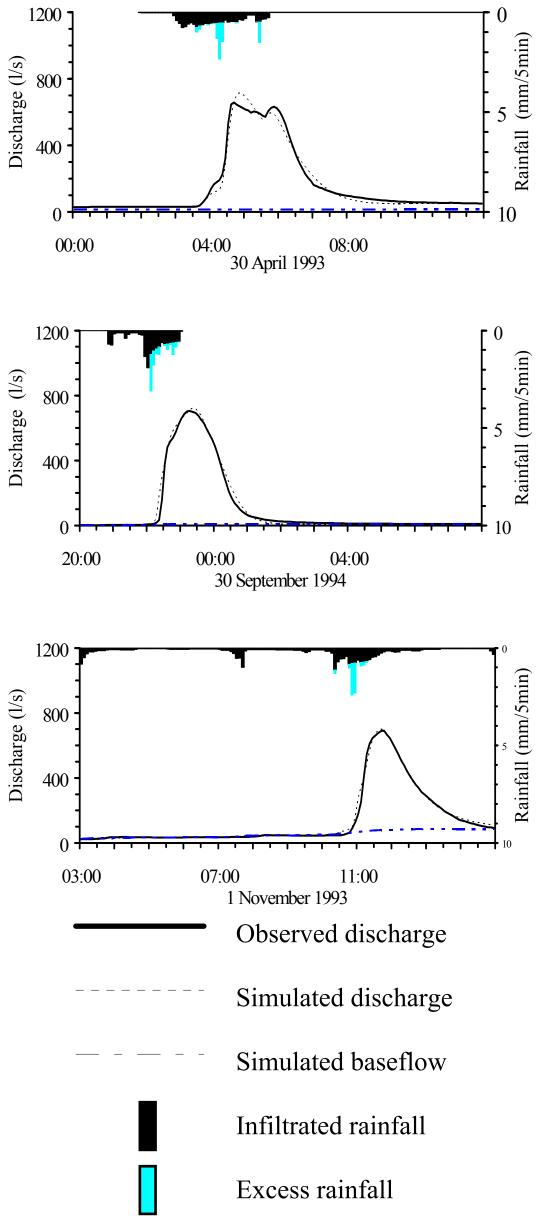

Figure 3: Hydrographs simulated at the Roujan basin outlet.

Figure 3 shows simulated and observed results for three flood events using a time step of calculation of 1 minute. The model enables to calculate, over each hydrologic unit, the part of rainfall that contributes to overland runoff (the excess rainfall) and the part that infiltrates to the groundwater aquifer. In the three flood events studied, the water table was high, and the ditches network drains the water table, and thus provides a basic water flow. If the water table is low, it encourages replenishment of the water table by reinfiltration of runoff.

6 CONCLUSION

The hydrological cycle in this farmed catchment under Mediterranean climate is dominated by intense and short rainfall events and Hortonian overland flow is the major process during flood events. Flood hydrographs are routed from each field part, through the ditches network to the catchment outlet. The network of human-made ditches appears to serve various purposes with regard to water flows. It accelerates runoff by concentrating flows and avoiding natural obstacles.

A spatially distributed hydrologic model linked to a GIS was developed to assess the role of human impact on the basin hydrology under Mediterranean climate especially the importance of the role of ditches network. Geographical Information System, here ARC/INFO, was used to subdivide the basin into hydrologic units. Hydrologic units were defined to take into account the characteristics of the agricultural domain especially ditches network and field limits. Each unit is described by hydrological parameters that depends on soil properties and agricultural practices (tilled and untilled fields). The hydrological model is deterministic non-linear model for conversion of rainfall into surface runoff and simulates Hortonian overland flow during flood events. The model enables to simulate flood events over agricultural catchments and is useful to simulate the long term geomorphic evolution of agricultural fields especially after land use changes.

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