RAINFALL-RUNOFF MODELLING ON SMALL PLOTS UNDER DIFFERENT LAND USES WITH A UNIT HYDROGRAPH APPROACH

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CIRAD CIMMYT INRA

Introduction

Modelling the rainfall-runoff transformation on small plots remains challenging. Two different approaches can be identified :

- 1/ fully mechanistic models modelling spatially variable overland flow (e.g. Fiedler, 1997) : as these models require a huge quantity of data they are used only at the very local scale (m^2). Moreover, infiltration process and crop growth are poorly or not accounted for.
- 2/ simple statistical models (e.g. Peugeot *et al.*, 1997) : they can be used on small plots or on hillslope, but only runoff amounts are simulated, thus the hydrograph at the outlet can not be obtained.

We propose to use a statistical approach based on the Unit Hydrograph (UH) model to quantify the effect of different forms of land use on runoff. This model has previously been used for watershed hydrology (Duband *et al.*, 1993) : it is called FDTF, for Fisrt Differenced Transfer Function.

Material and methods : experimental layout

CIRAD and INRA, working in collaboration with CIMMYT (Mexico), achieved a research project that aimed at characterising the effects of direct sowing with corn residues on water and nitrogen balances of the soil-mulch-plant system. The part that is presented here deals with the specific effects on runoff and is experimentally based on the following plots (figure 1):

- bare soil (lote6),
- unplanted soil covered with 1.5 t/ha maize residues (lote5),
- direct sown maize crop on soil covered with 1.5 t/ha maize residues (lote4),
- direct sown maize crop on soil covered with 4.5 t/ha maize residues (lote3).

Figure 1: Experimental runoff plots (from left to right lote1, lote2, lote3, lote4, lote5 and lote6).

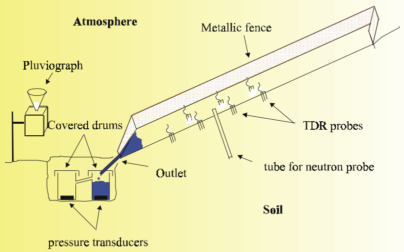


Figure 2: Instrumentation of runoff plots. Each plot is 10 m long and 2 m wide.

In practice, runoff was collected at the outlet of each plot in two successive drums. The water level in each drum was recorded with a pressure transducer at a dynamic time step ranging from 20 s during rainfall to 1 h. The first derivative of the signal was then calculated and smoothed to determine the runoff fluxes at the outlet of each plot. Rain was simultaneously measured with a pluviograph. Finally soil moisture was also estimated thanks to TDR probes and a neutron probe to assess initial conditions.

Material and methods : theory

The method is fully described in Duband et al. (1997) : only general features are summarised hereafter.
The rainfall-runoff process is splitted in two parts (figure 3) : **(i)** excess water is first generated as a fraction of the rainfall reaching the soil surface with a Production Function, **PF**, (excess rainfall, **ER**, is the part of the gross rainfall, **GR**, that is available for runoff); **(ii)** runoff fluxes at the outlet of the plot is then calculated from **ER** and a linear Transfer Function, **TF** (the TF is the same as the Unit Hydrograph). The basic equation of the method is the convolution equation between runoff fluxes and EP is :

$$Q_i^l = \sum_{j=1}^{K} TF_j \cdot ER_{i-j+1}^l$$

where Q_i^l is the runoff flux at time step i for rainfall event # l, K is the number of **TF** ordinates, ER_{i-j+1}^l is **ER** at time step $i-j+1$.

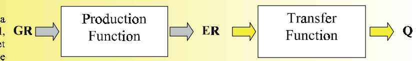


Figure 3 : ***Scheme of the model used in this study (UH approach)***

TF is linear and time invariant : for a given land use, the **TF** is the same for all rainfall events. The bulk of the non-linearity of the rainfall-runoff process is therefore concentrated in the **PF** : for a given land use, the **PF** depends on rainfall events.
The method does not require any arbitrary shape or analytical equation for the TF or PF. The method is supposed to provide : **(i)** set of ordinates for the TF associated with the land use, **(ii)** the series of **ER** associated with the rainfall events and associated with the land use. The iterative process is summarised in figure 4.

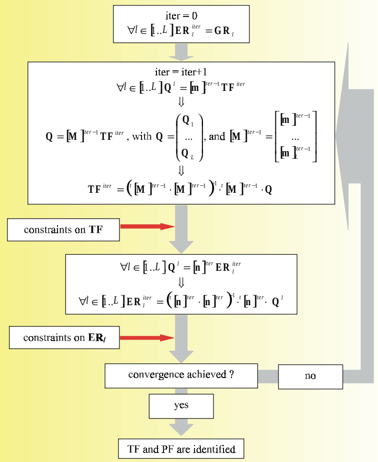
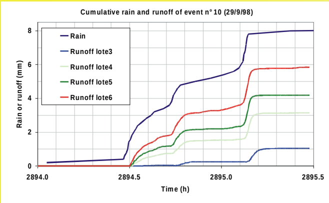
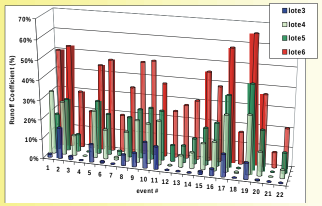


Figure 4 : *Scheme of the iterative procedure used in this study (FDTF)*

Before using the **FDTF** with the experimental data, we checked the consitency of the method with generated runoff events. A theoretical **PF** was applied to the experimental gross rainfalls, which gave theoretical excess rainfalls. These ER were convoluated with a theoretical **TF** to generate theoretical runoff. Then, using the experimental gross rainfalls and the generated runoff fluxes as input values, we ran **FDTF** to derive calculated **PF** and **TF** that were compared to the imposed theoretical functions.

Results : experiments

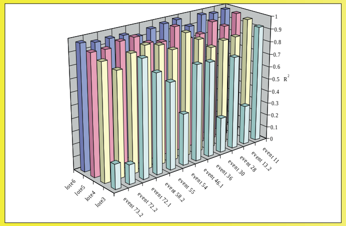


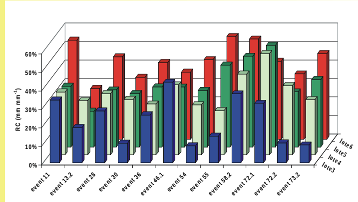


These experimental results show that:

- bare and crusted soil (lote6) always has the greatest runoff coefficient (RC), ranging from 8% to 65%,
- a small quantity of corn residue (lote5) induces a strong runoff decrease (0%<CR<43%), by increasing pathways tortuosity, slowing the flow and improving infiltration rate thanks to soil protection,
- a plant effect can be pointed out comparing lote4 and lote5, especially in the second part of the cycle when the crop is well developed. Soil protection, runoff interception, stemflow and modification of soil moisture are the main factors that contribute to this effect,
- a strong mulch density effect can be observed between lote3 and lote4. Runoff coefficient is often 0% and never exceeds 16% for lote3. The latter is always significantly higher for lote4 (0%<CR<32%).

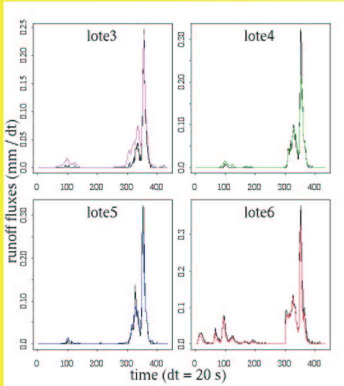
Results : modelling

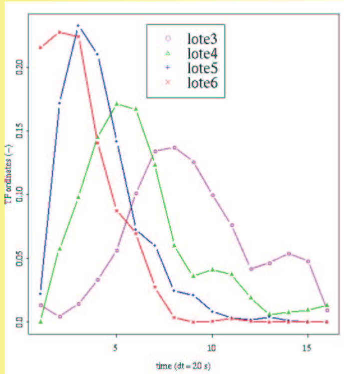




Simulated runoff coefficients for the different experimental plots

For all experimental plot, except lote3 (cropped plot with 4.5 t ha^{-1} residues), and for all rainfall-runoff events the determination coefficient R^2 of the linear regression between simulated and experimental runoff fluxes is always > 0.8, which shows a good modelling of the rainfall-runoff process. For lote3, runoff is always overestimated by the **FDTF**. Anyway, runoff amounts are very low (< 1mm very often) for this plot.

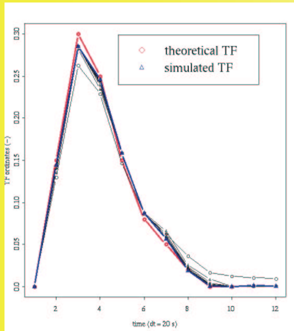


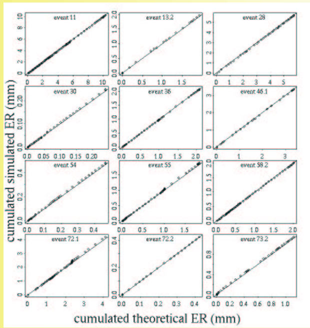


To illustrate the accuracy of **FDTF**, we plotted the experimental and simulated runoff fluxes for the different plots for rainfall event # 11. The shape of all the hydrographs is well simulated. Runoff amounts calculated by the model are in agreement with the experiments for all plots but lote3. In this case, the discrepancy is mainly due to overestimation of **ER**, the shape of the hydrograph being well simulated.

On this graph we plotted the **TF** (or Unit Hydrograph) for the different treatments. **TF** for lote6 is narrow and very sharp: runoff at the outlet of the plot is simulated as soon as excess rainfall appears and disappears within 7 time steps. It implies that water flows quickly at the soil surface and along straight pathways. **TF** for lote3 is broader with a lower peak: runoff is delayed and spread over more than 10 time steps, which suggest that water flows more slowly along more tortuous pathways. These results are in agreement with experimental measurements and observations.

Results : validity of the method





Convergence of **FDTF** was achieved within 11 iterations. The **TF** is very well simulated: the shape and the peak of simulated and theoretical **TF** are similar. Cumulative simulated **ER** is plotted against cumulative theoretical **ER**: the points stay along the 1:1 line, which shows that the theoretical **PF** is well simulated by the model. We consider that it proves that **FDTF** is a consistent model.

Conclusion

FDTF was previously applied at the catchment scale (Duband *et al*., 1993). We showed that it can also perform well at the plot scale. Thanks to **FDTF**, we could quantify the effects of land use on runoff generation (**Production Function**) and runoff transport (**Transfer Function**). This quantification enabled us to classify the plots: **FDTF** proves to be a good classification tool.
More research is needed to link simulated **PF** and **TF** to physical features of the different plots (infiltrability, soil surface roughness, crop growth, ...).

References :

Duband, D.; Ch. Obled and J.Y. Rodriguez, 1993. Unit hydrograph revisited: an alternate iterative approach to UH and effective precipitation identification, *Journal of Hydrology*, 150,115-149.

Fiedler, F.R., 1997. Hydrodynamic simulation of spatially variable overland flow. PhD Thesis, Colorado State University.

Peugeot, C.; M. Esteves, S. Galle, J.L. Rajot and J.P. Vandervaere, 1997. Runoff generation processes: results and analysis of field data collected at the East Central Supersite of the HAPEX-Sahel experiment, *Journal of Hydrology*, 188-189, 179-202.