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APPLICATION OF CELLULAR AUTOMATA MODELLING TO ANALYZE THE DYNAMICS OF HYPER-CONCENTRATED STREAM FLOWS ON LOAMY PLATEAUX (PARIS BASIN, NORTH-WEST FRANCE)

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For several years, flash floods appear frequently on small dry valleys of the Paris Basin, in the North of France. These “hyper-concentrated stream flows” are defined as floods with sudden apparition, rapid rising time and important specific flow. They are produced by intense rainfall (>50mm.h^{-1}) over small areas (<40km²) and present single features. The catchment morphology is a first-order controlling factor of floods dynamic. For a better understanding of such type of processes, analysing the morphological signature of these catchments becomes of paramount importance. Therefore, classical morphometric methods do not consider the dynamics generated by the catchments structure. So we develop a new tool based on spatial analysis and the cellular automata “*Ruicells*” is proposed. It allows us to integrate the catchment geometry, the slopes pattern and the drainage network in order to simulate runoff response at different outlets. First results attempt to validate the influence of drainage network on the hydrological response of the catchments, while size of drainage area has a minor influence. Moreover, the application of cellular automata modelling highlights the causes of spatial and temporal variability of flows as for example the relation between the location of streaming areas and water paths.

INTRODUCTION

Over the last decade, flash floods appear frequently on small dry valleys of the loamy plateaux in the North of France. Classically called “muddy flows”, “turbid floods” or “mudslides”, the classification of "hyper-concentrated stream flows" is preferred in this paper. Such type of processes are defined as floods with sudden apparition, rapid rising time (<20mn), extremely violent onset and important specific flow.

Stream flows presents single features in these regions. Classically, they are produced by paroxystic meteorological events concentrated in only a few hours (>50mm) over small areas (<40km²). The groundwater is not usually saturated, but the infiltration rate is much lower than the rainfall rate. Although floods occurred in a relatively small area, water production and runoff routing can be so voluminous that such a flood wave can propagate very quickly. For example, the June 16th 1997, a 1m-surge has quickly rushed down the Vallon of Ouraille (317ha), located in figure 2, and many cars were carried out.

The majority of these floods are related to land use, agricultural practices and soil erosion. The relationships are obvious because soils provide materials which explain the turbidity of stream flows. Although these floods are linked to a paroxystic soil erosion appearance in many studies (Nachtergaele *et al* [1]; Le Bissonnais *et al* [2]; Poesen *et al* [3] for recent reviews), less research has focused on the catchment morphology. Therefore, it has yet been recognised that, during an intense and localised thunderstorm, the dominant runoff processes generated stream flows are strongly influenced by the physical characteristics of the catchments and their orography (Najani [4]; Kirkby *et al.* [5]; Soulsby *et al.* [6] for recent studies). Classically, the morphological structure and the spatial organisation of the catchment determine the distribution of water flow paths and runoff processes. Instead, the influence of catchment morphology has been minimized in these regions because of weak-slope gradients and oceanic climate without extreme events. Nevertheless, some studies have underlined the contrary (Delahaye [7], [8]).

For a better understanding of such type of processes, analysing the morphological structure of these catchments becomes of paramount importance. Many studies measure the catchment morphology using several morphometric indices. One major state of the art is well described by Zavoianu [9]. Nonetheless, these classical morphometric methods are limited to the description of catchment characteristics (shape, slope and network) in a static way and do not consider the dynamics generated by the morphological system. So the main objective of this research is to propose a tool which aims at modelling hydrological dynamics with catchment morphology parameter. A new methodology based on spatial analysis and a cellular automaton model is proposed.

DESCRIPTION OF THE MODELING APPROACH

The following analysis was carried out to find a coherent measurement of the influence of morphological system on its hydrological dynamics. Many efforts have recently been made to determine the relationships between morphometric parameters and runoff response using various methods (Rodriguez-Iturbe and Rinaldo [10]; Tucker *et al.* [11]; Ivanov *et al.* [12]; Snell *et al.* [13]). In spite of these recent tools, no method can translate the major influence of catchments morphology on runoff routing in a dynamic way. Accordingly, a new methodology based on cellular automata appears more relevant.

Initially, it was necessary to generalize the traditional concept of cellular automata (Langlois and Phipps, [14]) to implemented the variable geometry of the TIN surface (Triangular Irregular Network), through surface cells (slopes), linear features (stream network) and specific nodes (closed depressions), and in the same time the connectivity between these cells. Flow pathways cannot be guided uniformly by the rules of vicinity of the cellular network. Nevertheless, they depend in this model on the morphological links structuring the TIN surface. This assumed approach is thus based on a generalized cellular automaton in which cells have forms and variable size (point, line, surface), and whose flow pathways permit translating the real morphological structure of surface and not only its topology. Delahaye *et al.* [8] and Langlois and Delahaye [15] give more details on the construction of the surface flow network of this automaton.

According to flow pathways defined in the graph, the cellular automaton allows routing any kind of quantitative information through cells. In this study, the surface which is the first information contained in cells is mainly used. At each iteration, i.e. step of simulation, all the cells are drained in those which are connected at the downstream. Even if it is inconvenient to treat time as discrete, the advantage of this method is that cells receive and summarize surfaces coming from the upstream, e.g. see figure 1. The simulation is finished when all surfaces has forwarded by the point of measurement, i.e. when the most distant surface of the catchment has just passed to the outlet.

Several simulations are possible according to starting parameters. On one hand, the sum of surfaces is calculated from the number of cells crossed during the simulation. In this case, the number of iterations is practically equal at the distance to the point of measurement. Obtained curves approach "width function" of Shreve or "distance-area function" defined by Rodriguez-Iturbe and Rinaldo [10]. Results should be similar if a regular mesh was used. On the other hand, the slope is integrated. The sum of surfaces is then summarized according to the travel time. The time of transit is obtained with the average flow velocity and depends on the slope of each cell.

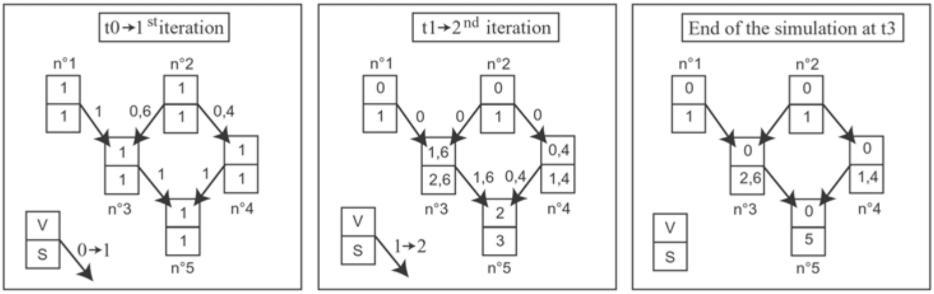

Figure 1. Schematic structure of the routing scheme of "Ruicells". The top of box (V) corresponds at surfaces inputs in cells per iteration; the bottom of box (S) summarizes the cumulative sum of surfaces drained in each cells at the end of simulation. And values out of the box indicate surfaces flows between the two iterations t*n* and t*n+1*.

Results of the second simulation testify both the effect of the catchment shape in a 2D dimension, and the role of relief on hydrological dynamics in the 3D.

Finally, this procedure allows analysing each morphological variable (shape, slope, drainage network) and its influences on surface routing. The other advantages of such a method are that it permits the association of all components in a synthetic morphological system, and we can better explain its role on the hydrological response of a catchment. Moreover, outputs of simulation posts surface flow charts with coloured classes whose represent cumulative surface crossed in each cell. Obtained map presents the preferential water flow paths and its organization. Numerical files have also been preserved at the end of simulation. One of them gathers especially the values of surface crossed at each step of simulation for chosen points of measurements, assimilated at different outlets. By convenience, the curve representing uniquely surface flows is called "surfaçogramme", whereas the other curve which integrates the flow velocity names "morphogramme".

CHARACTERISATION OF THE MORPHOLOGICAL SYSTEM DYNAMIC

The study was undertaken in four catchments where a hyper-concentrated stream flows occurred for recent years. Analysis has been carried out on areas ranging between 10 and 40km², all located in the North of Paris Basin in France. They are named AIZ [Aizelles], LEZ [Lézarde amont], SMB [Saint-Martin de Boscherville] and ESS [Essômes s/ Marne]. Figure 2 presents mapping of surface flows obtained for chosen catchments at the end of surfaçogramme simulation. As can be seen, the shape of AIZ and LEZ appears almost triangular and compact, whereas the shape of SMB and ESS seem more elongated.

Topographic characteristics and results of simulation are summarized in Table 1. The scaling effect in the hydrological response of catchments is very significant. The smaller catchment AIZ has a little time of concentration, with weak and rapid hydrograph peak (10,6ha) attempted at the 53rd iteration. Conversely, the catchment LEZ renders large time of concentration and long-duration time to peak (25,1ha at the 97th iteration). It is important to notice that results indicate varying surface response due to the specific morphological conditions. The discharge peak does not always increase proportionally to the catchment size. This is particularly true for SMB and LEZ catchments. While the size of SMB area is larger, its peak is less important (16,8ha) and its rising time longer.

Table 1. Simulation and topographic results (with units) for chosen catchments: area (*A*), peak discharge (*Qp*), time of concentration (*Tc*) and time to peak (*Tp*).

Catchment list	*A* (km²)	*Qp* (ha)	*Tc* (iterations)	*Tp* (iterations)
AIZ (Aizelles)	4,1	10,6	88	53
LEZ (Lézarde amont)	13,4	18,1	152	100
SMB (St-Martin de B.)	14,3	16,8	182	129
ESS (Essômes s/Marne)	21,3	25,1	192	97

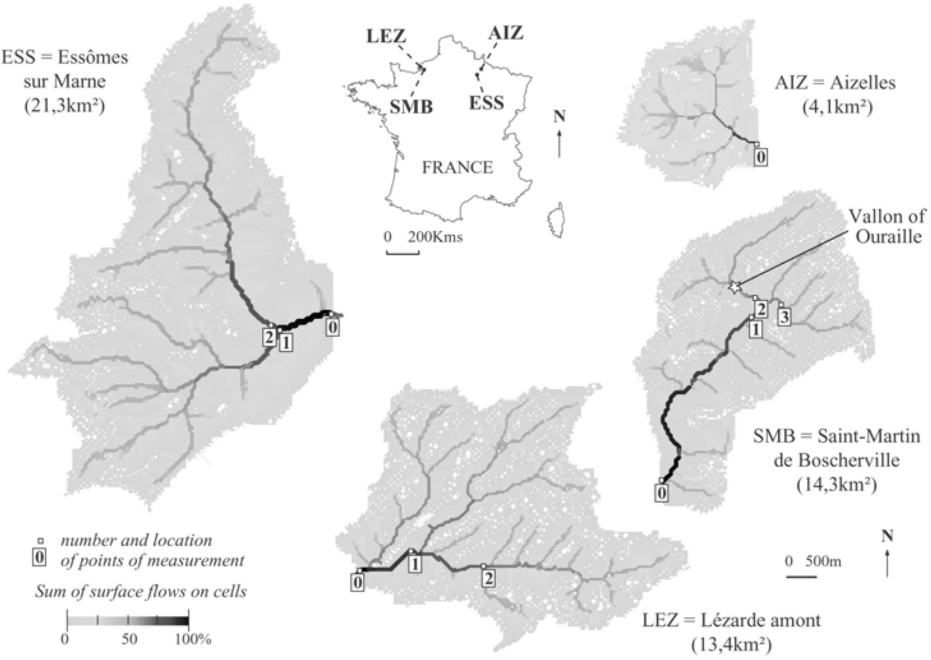

Figure 2. Results of surface flows mapping for chosen catchments obtained with Ruicells.

As the model registers surfaces data in each outlet using the same steps, a discharge hydrograph of surface flows can be made to analyse the hydrological response, e.g. see figure 3a. The curves of surface flows discharge measured at the outlet of AIZ, ESS and LEZ catchments present regular increasing- and rapid decreasing- discharge. Efficiency of the most circular shapes that can be assimilated at “pear shapes” explains such rapid response. At the opposite, the curve obtained for SMB indicates a chaotic response because of disordered surfaces and non-hierarchical drainage pattern. This configuration reduces the discharge peak and lengthens the time of concentration.

Surface flow mapping and the discharge hydrograph allows a first analysis of various hydrological responses. This methodology can mainly account for relevant morphological signature. The catchment LEZ has a very specific organisation of its drainage pattern, e.g. see figure 3a. All networks are oriented towards the same point and patterns convey surfaces with a minimal loss of energy at final outlet. Such hydrological structure is generally the result of an internal homothetic behaviour witch makes response very effective as quote Rodriguez-Iturbe and Rinaldo [10]. Therefore, SMB behaviour depends on one upstream part of the catchment and its time of concentration seems to be longer because of an ineffective downstream part. Furthermore, more information is needed to quantitatively dissociate the sub-catchments contributions in order to correctly analyse the hydrological response measured at the final outlet of catchment.

In this following, discharge hydrographs have been made for several outlets. Results show both the combining contributions of tributaries and their efficiency to the peak discharge. Surface flows of the catchment ESS are carried out along two links of same length with which the two individuals peaks are summarized to form the peak of 25,1ha (12,9 + 12,1), e .g. see figure 3b. Constant surface flows also explain the peak simulated at the final outlet of the catchment LEZ. The upstream part of the two sub-catchments n°1 and n°2, located on figure 2, are together efficiency and produce a strong peak with the first sub-catchment contribution, e.g, figure 3c. Hence, rising peak waves which move through well-hierarchical drainage pattern induce a strong peak at the final bifurcation.

Results for the catchment SMB vary considerably. The time to- and discharge- peaks are uniquely linked to the upstream part of the point n° 2. The contribution of the upstream part of the sub-catchment n°3 is especially efficient. Indeed, this compact shape provides a peak of 10,9ha while its area accounts for 23% of the total catchment area, e.g. see figure 3d. The discharge increasing is stronger and has even a smaller duration than that simulated for the outlet of the catchment AIZ. Fortunately, the rising peak waves simulated for the sub-catchments n°2 and n°3 are not correlated both in time and space.

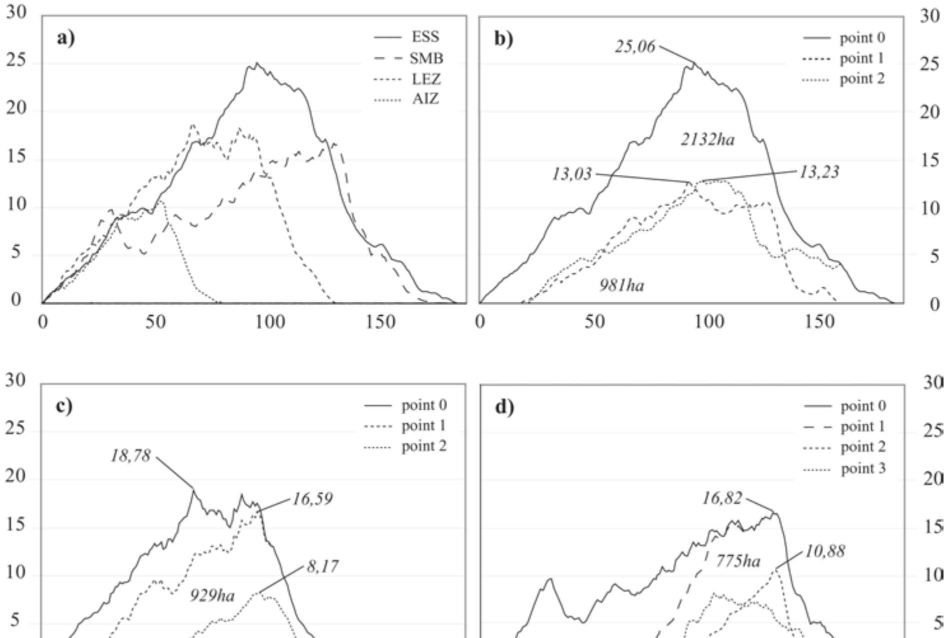

Figure 3. a) Simulated surfaçogrammes for chosen catchment using surface flows (in ha) per iteration; The other graphs show rising peak waves and sub-catchments contribution to the discharge of surface flows simulated for the ESS (b), the LEZ (c) and the SMB (d).

CONCLUSION: MODEL RESULTS AND PRACTICAL USE

After modelling hydrographs on several catchments, it appears that the organisation of drainage patterns, i.e. the relationships between catchment size, network, surfaces and their distance to the outlet, is more significant than the catchment area. This link has remained a theoretical suggestion during a long time. Hence, such a cellular automaton application aids to better define various morphological systems. Model outputs lead to identify tributaries contributions and the location of rising peak waves. It does provide a mean establishing the influence of catchment morphology on its hydrological dynamics.

Moreover, results show that the concept of catchment area, defined as a spatial unit of reference in most hydrological studies, is not so relevant for such type of processes. Generally, a catchment and its tributaries are arbitrarily defined by the upstream part of chosen outlet. However, we see in this study that combining contributions of tributaries and their distance at the final outlet are more important that the catchment scale. The case of the SMB catchment is significant. Flash flood damage that occurred after a storm of about 80mm within 6 hours in the evening of June 16th 1997 was very dramatic in the upstream part of the point n°2, e.g. see figure 4, but less at the final catchment outlet.

Major effort should also be put to guide future analyses on the incidence of "active morphological areas" in the particular case of "hyper-concentrated stream flows". The proposed methodology based on a cellular automaton allowed identifying such type of functional areas and a good concordance between model simulations and a few runoff measurements has yet been observed. Other applications should lead to analyse the spatial distribution of streaming areas according to the morphological system dynamics.

Figure 4. Off-site damage photos in the Vallon of Ouraille during flash flood of June 16th 1997: rising wave arriving at the paroxystic moment of the flash flood (a) and velocity of rising waves after the peak discharge (b) in the upstream part of the point n° 2.

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