# Use of cellular automata in physical geography

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# CELLULAR AUTOMATA IN PHYSICAL GEOGRAPHY

## Use of cellular automata models for assessing impacts of morphology on catchment hydrology during hyper-concentrated floods (Paris Basin, France).

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### ABSTRACT

Hyper-concentrated floods are events regularly affecting during spring and summer the loamy plates of the Paris Basin, in North-West France. Such floods are characterized by sudden triggerings, fast rising times and important specific discharges. According to high rainfall rates, morphology is well-identified as the first-order controlling factor on floods dynamics, while cultivated areas and land use aggravate its influence in a second order. Traditionnal morphometric indexes are generally used to quantify effects of catchment form, slopes or the drainage network on hydrological processes. Therefore, these tools present important drawbacks. Indeed, they do not consider the dynamics generated by the structure of the catchments and they have been created in static planar dimension. Thus, influence of morphology on catchment hydrology has to be re-evaluated and we propose in this study a cellular automata application. *RuiCells* integrate the catchment geometry, slope patterns and the drainage networks at a cellular scale to simulate the influence of topography on the surface flow dynamics at the overall catchment scale. Results were that: i) the influence of the spatial organisation of cells within the catchment and their connection to the drainage network is more important than the catchment size; ii) simulations reveal the intrinsic relationships between functional morphological areas and water paths; iii) spatial scaling effects and hydrological behaviours are recognized at the global scale but a small catchment part can induce violent hydrological response. Combinations between topography, runoff contributing areas and slopes seem to explain complex concentrated flow distributions in time and space.

### KEYWORDS

Hyper-concentrated floods, catchment morphology, dynamic simulations, Cellular Automata.

### BACKGROUND

Hyper-concentrated stream flows are common events on loamy plateaux of the Paris Basin, North Western France, over the last 20 years (Delahaye et al. 2001 [1]). During the period 1983-2005, 345 incidents of damage to property by muddy runoff and 187 catchments affected by violent flows have been registered (Douvinet et al. 2007 [2]). Such floods present single features quite those different from other regions. They are characterized by a sudden triggering, a rapid rising time and important specific discharge. Paroxystic meteorological events provide high rainfall quantities (50-150mm) in just a few hours (less than 6 hours). Consequently, hydrological conditions are dominated by important overland flow due to a rapid saturation on surface of loamy soils. Sensitivity of soils in response to high rainfall intensities is elsewhere well known since the 1990's years (Ouvry, 1990; Ludwig, 1992; Auzet et al., 1995, in Souchère et al., 2005 [3]). Even if affected areas are of small sizes (<40km²), the rapid runoff concentration currently involves a sudden rising peak wave and dangerously, a surge may rush down the main dry valley just a few minutes after the peak of rainfall. These processes are often described like "mud flows", "muddy flows" (Boardman et al., 2003 [4]) or "muddy floods" in other environments because of the high suspended sediment content. However, the term of “hyperconcentrated stream flows” may be preferred according to various rheological classifications of Pierson and Costa or of Coussot and Meunier (Douvinet et al., 2006 [5]). Even if hydrological conditions are now well known, dynamics and hydrological processes still remain misunderstood for several reasons.

## PROBLEM STATEMENT

Use of one Cellular Automata model seems to be a good opportunity for following reasons:

1) Floods currently appear on dry valleys where no gauging data exist because of the small catchment sizes (<40km²) and due to the absence of permanent stream flows in valleys inherited of periglacial conditions. As hydrological data miss, modeling or simulating tools are needed.

2) Even if numerous morphometric methods have been created to describe the influence of topography on catchment hydrology (Zavoianu, 1985 [6]), they present important drawbacks. i) Each index measure one of the tree morphological components (catchment shape, slopes, drainage network) but none appreciate the morphological system in its globality. ii) They don’t consider the dynamics generated by the structure of catchments from local to global scales. iii) They have been created in a static planar way and some studies demonstrate the scaling dependency and poorly significance of several indexes (Douvinet et al., 2006 [5]).

## METHODOLOGY FRAMEWORK TO ANSWER TO A GEOGRAPHICAL PROBLEM

Cellular Automata (CA) are not often used in geographical studies. Recent reviews have therefore recently underlined interests and advances in many applications (Fonstadt, 2006 [7]). Using a common language to others, our CA model “RuiCells” (*Ruissellement sur Cellules* in French language) was developed to find an iterative method to measure the influence of each morphological component of a geographical space on surface flow paths. It was first used for simulating runoff on cultivated areas in a predictive way, and the main difficulty was linking topographic variables and hydraulic variables such as water fluxes (Figure 1). In this second application, we want to test impacts of catchment morphology on theoretical surfacic response.

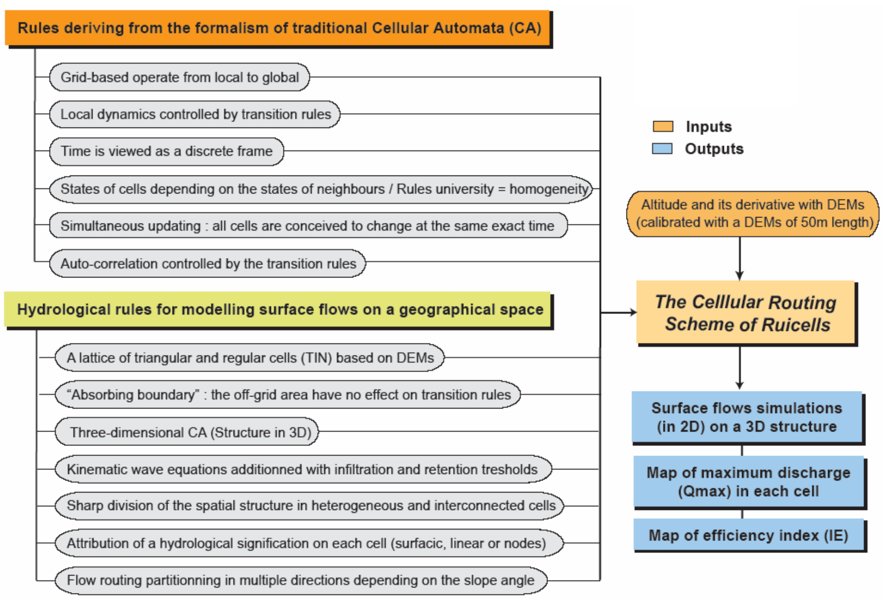


Figure 1: Input and output parameters implemented in RuiCells for surface flow simulations

As results, Ruicells is like a mixture of traditional CA rules (Wolfram, 2004) and the multiple transformations required for the modelling of hydrological processes on a geographical space. It should be more convenient to prefer the term of “Geographical Cellular Automata” (GCA) to design such tool modified to answer to a geographical problem (Ménard and Marceau, 2006 [8]). The topological mesh and hydrological rules are more detailed in another paper Langlois and Delahaye (2002) [9]. The Cellular Routing Scheme (CRS) of Ruicells depends on the surface flow from each cell and on the updating of the values of all the sub-states [also called iterations]. Interestingly, automaton allows routing simultaneously various quantitative data (i.e. surface, flows, rainfall, etc) from cell to cell until the final downstream cell will reach. Other simulations can integrate land use, runoff coefficients or artificial pattern as roads or tillages.

**RESULTS**

We uniquely studied surface influence. Upstream surfaces are first computed on each cell at the end of simulations (Figure 2A). These maps allow following surface flows routing at each length-step defined by the mesh scale. Results show roles of the spatial organisation between surfaces but they do not represent the real drainage network. We also propose other maps representing the distance of cells from the outlet of the catchment thanks to the Cellular Routing Scheme (Figure 2B). Such an approach allows involving the “isochronous” curves method and mainly highlights areas with important morphological efficiencies. All the “blue” cells, well-connected through the drainage network, are areas which explain the theoretical response at the global catchment scale (Figure 2C).

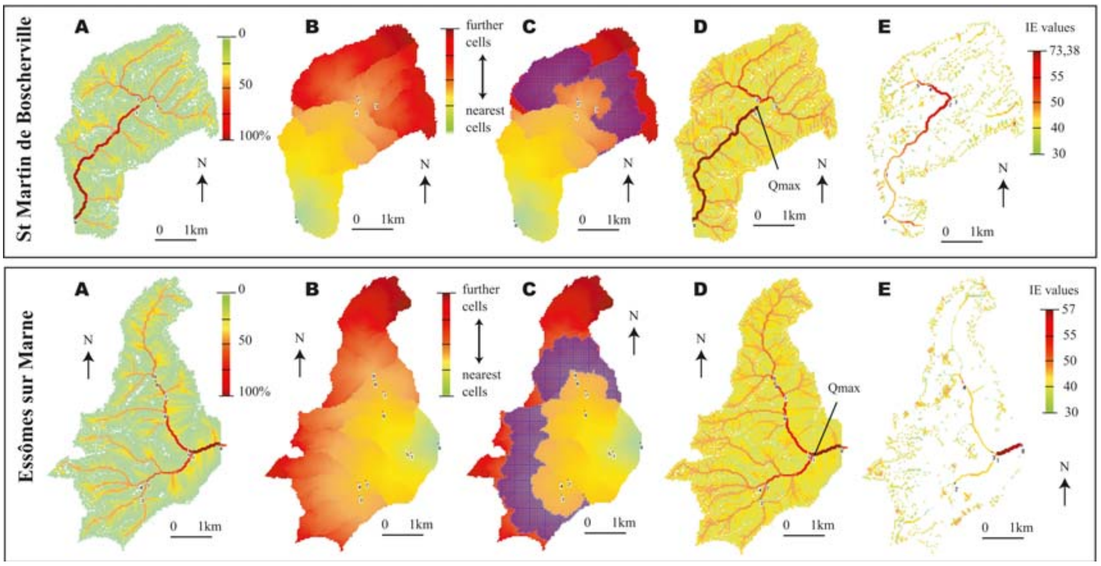


Figure 2: Simulation mappings representing: A/ the upstream surface on each cell relating to the whole area; B/ the distance of each cells since the final outlet; C/ efficiency areas; D/ the maximum surface flow discharge on each cell; E/ critical points with IE values (=maximum discharge values v.s. the upstream surface) traducing a strong energy.

Maps lead to question the catchment scale as the reference scale to study these processes. While efficient parts are often hidden within the catchment at the global scale, this approach allows detecting energic points with the help of one index IE. This IE index is calculated using the maximum surface flow discharge (Qmax) versus the square root of the upstream surface x 100 (Figure 2D and 2E). Values >50 localize points with high efficiency (Figure 2E). In the two catchments, single features appear: In St Martin, efficient areas are located in the upstream part whereas in Essômes, the organisation of drainage network at the overall scale provides an important and strong response uniquely at the final outlet. Interestingly, maps show specific behaviours characterized by strong morphological reactivity which in reality corresponds to areas where damage was important during violent floods. Finally, such a tool show interconnections from the local to global scale between surface flows, drainage networks and slopes. Now, these efficient points have to be compared to real flows (a difficulty in dry valleys…) or to the importance of morpho-dynamical impacts observed during hyper-concentrated floods (Douvinet et al., 2007).

## CONCLUSIONS

Within catchments, sensitivity to various factors varies considerably and induces important difference degree in damage and intensity during hyperconcentrated floods in this region. The Geographical Cellular Automata (GCA) "Ruicells" is used in this study to demonstrate the presence of efficient morphological areas and strong spatial reactivity of several spatial configurations. Simulations on these two catchments show that catchment response, driven by high rainfall rates and conditioned by land use covers, is strongly dependant on catchment morphology. Other simulations also illustrate the role of topography on catchment hydrology during these hyperconcentrated stream flows characterized by important runoff flow pathways.

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