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15th European Colloquium on Theoretical and Quantitative Geography
7-11 september 2007 in Montreux Switzerland

USE OF CELLULAR AUTOMATA IN PHYSICAL GEOGRAPHY

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

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1. CA CONTRIBUTIONS IN PHYSICAL GEOGRAPHY

Recent advances in physical geography : A brief review

CA methods for **describing physically deterministic systems** or for **testing research hypothesis** have become much more accurate in **physical geography and geomorphology** since a few years.

Some of the early researchers in geomorphology were researchers who built **landslide** and **debris-flow simulation** (Di Gregorio et al., 1994) after the original **sandpile CA** of Bak et al. (1987). These simulations have been extended to include **lava** (**SCIDDICA**) and **pyroclastic flows** (**SCIARA 2**).

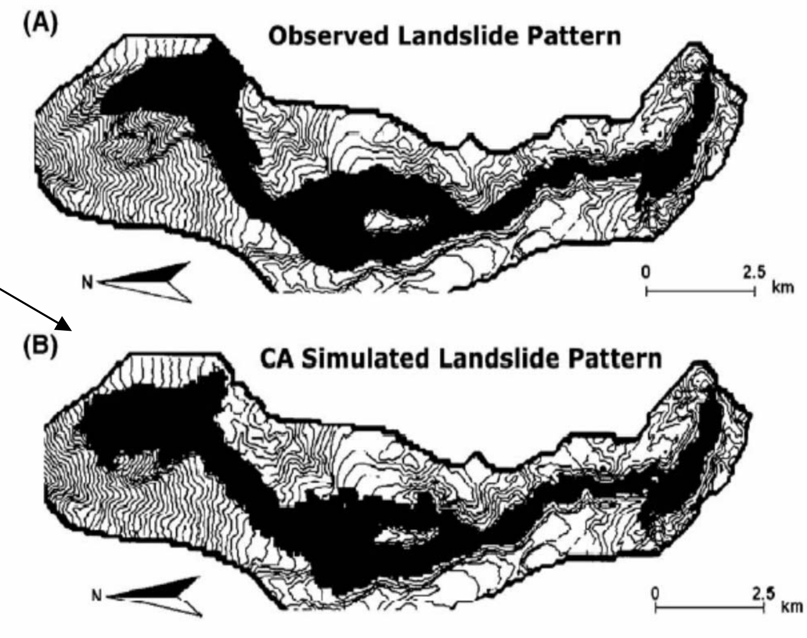
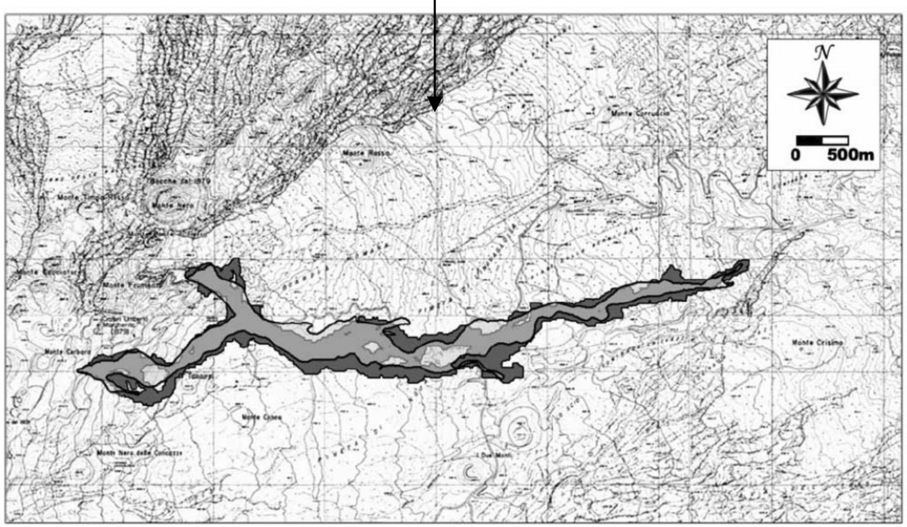


Fig. 3. (A) Observed and (B) CA-simulated landslide paths, from D'Ambrosio et al. (2003).

D'Ambrosio et al., 2003



Avolio et al., 2006

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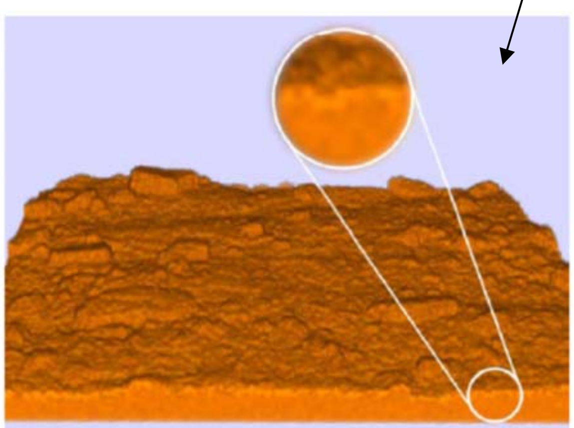
1. CA CONTRIBUTIONS IN PHYSICAL GEOGRAPHY

Numerous and diversified applications

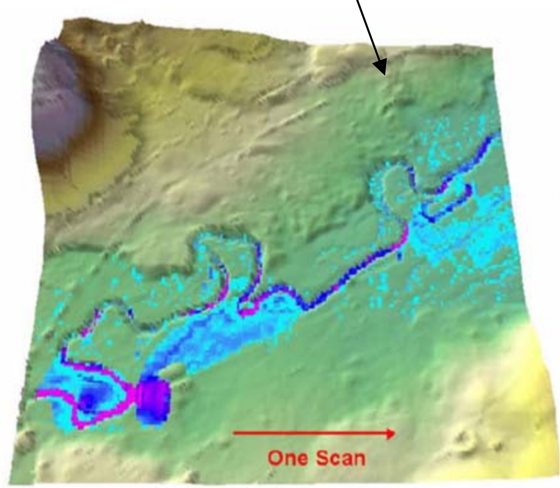
Research has since expanded to various geographical objects :

- **eolian ripples and dune formation ;**
- **embedding reach scale in fluvial rivers** (**CAESAR**)
- **transport and sediment flow** in floodplain (**CAESAR**) ;
- **landscape evolution** (**LANDSAP**) ;
- **rainforest dynamics** (**DivGame**) ;
- **soil crust and erosion** at plot scale (**SoDA**)

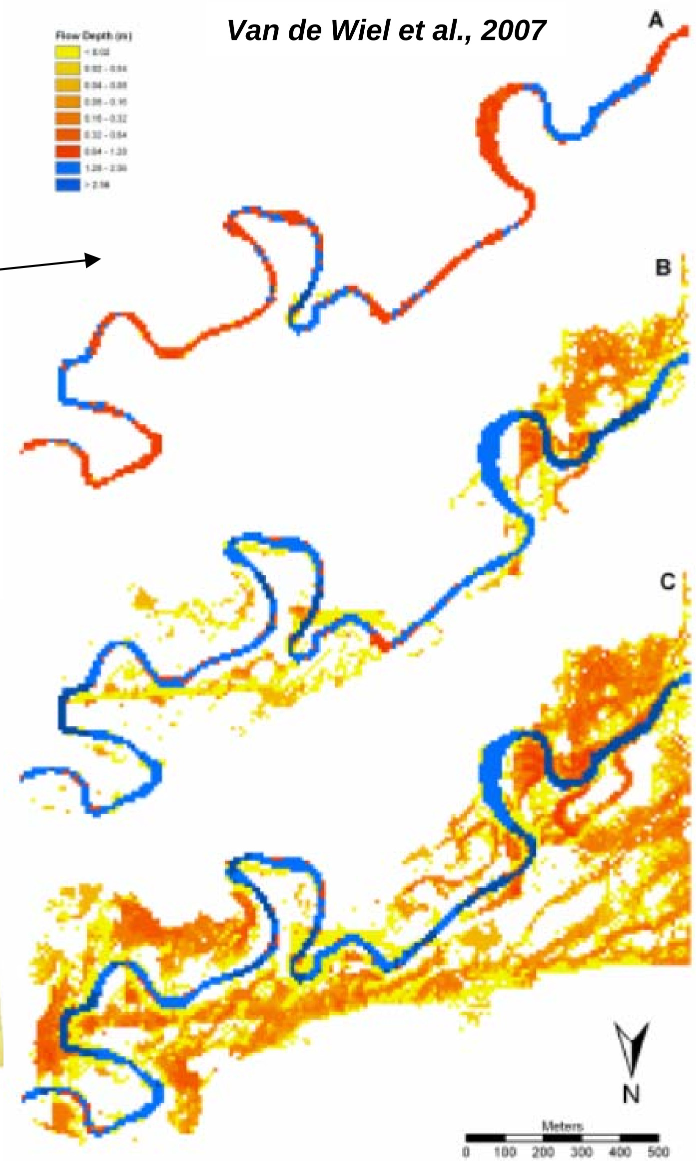
…. and all others!!!



Vallette et al., 2007



Coulthard et al., 2007



Van de Wiel et al., 2007

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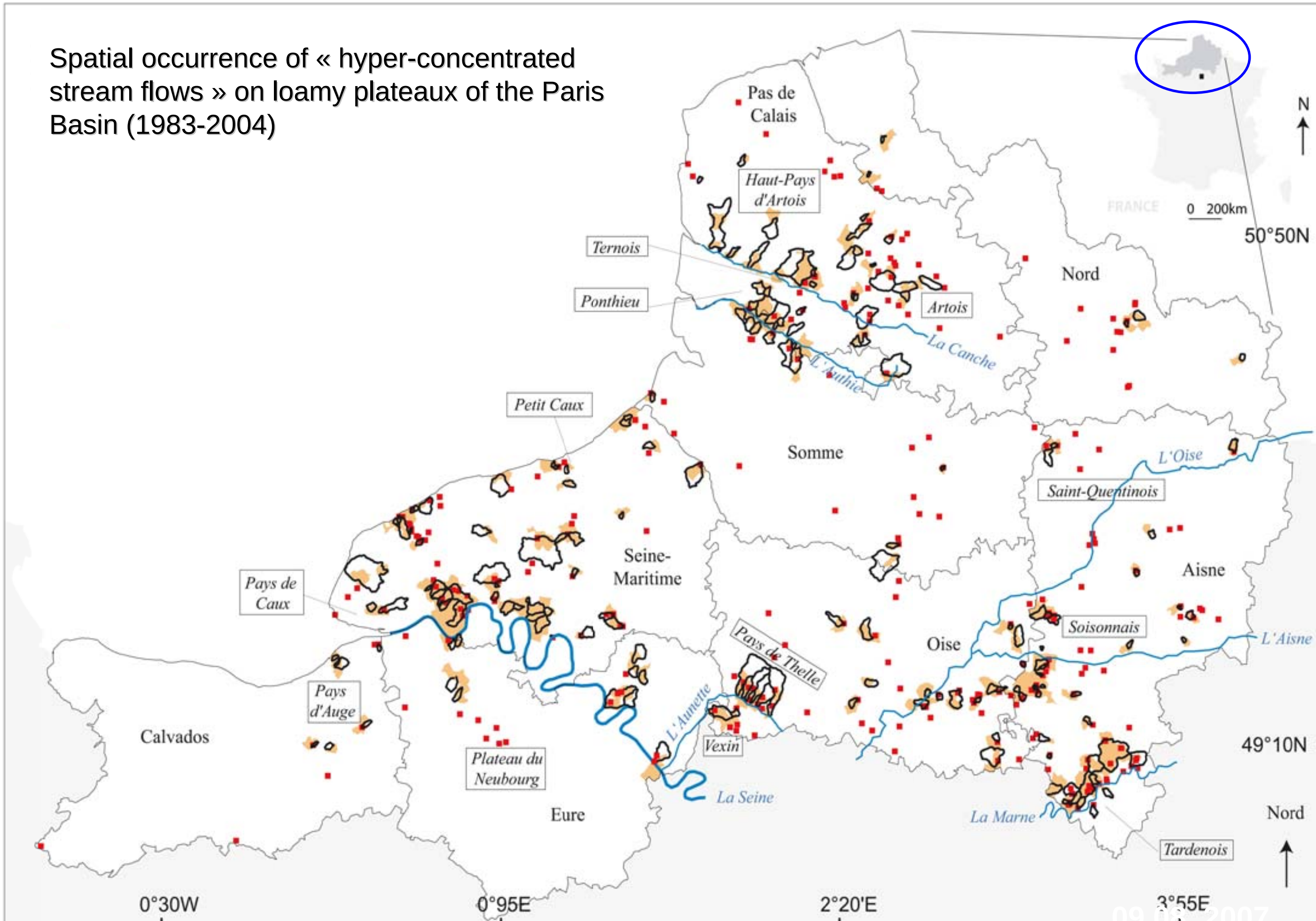
2. BACKGROUND

Hyper-concentrated floods are flow phenomena widely observed

Such **flash floods** are currently observed on valleys being part of loamy plateaux of the Paris Basin : **191 affected areas** have been registered in the North of France over the period 1983-2005.



Spatial occurrence of « hyper-concentrated stream flows » on loamy plateaux of the Paris Basin (1983-2004)

- Localized runoff phenomena
- **Sensitive catchments**
- **Sensitive cities**
- Vexin — Sensitive agricultural area

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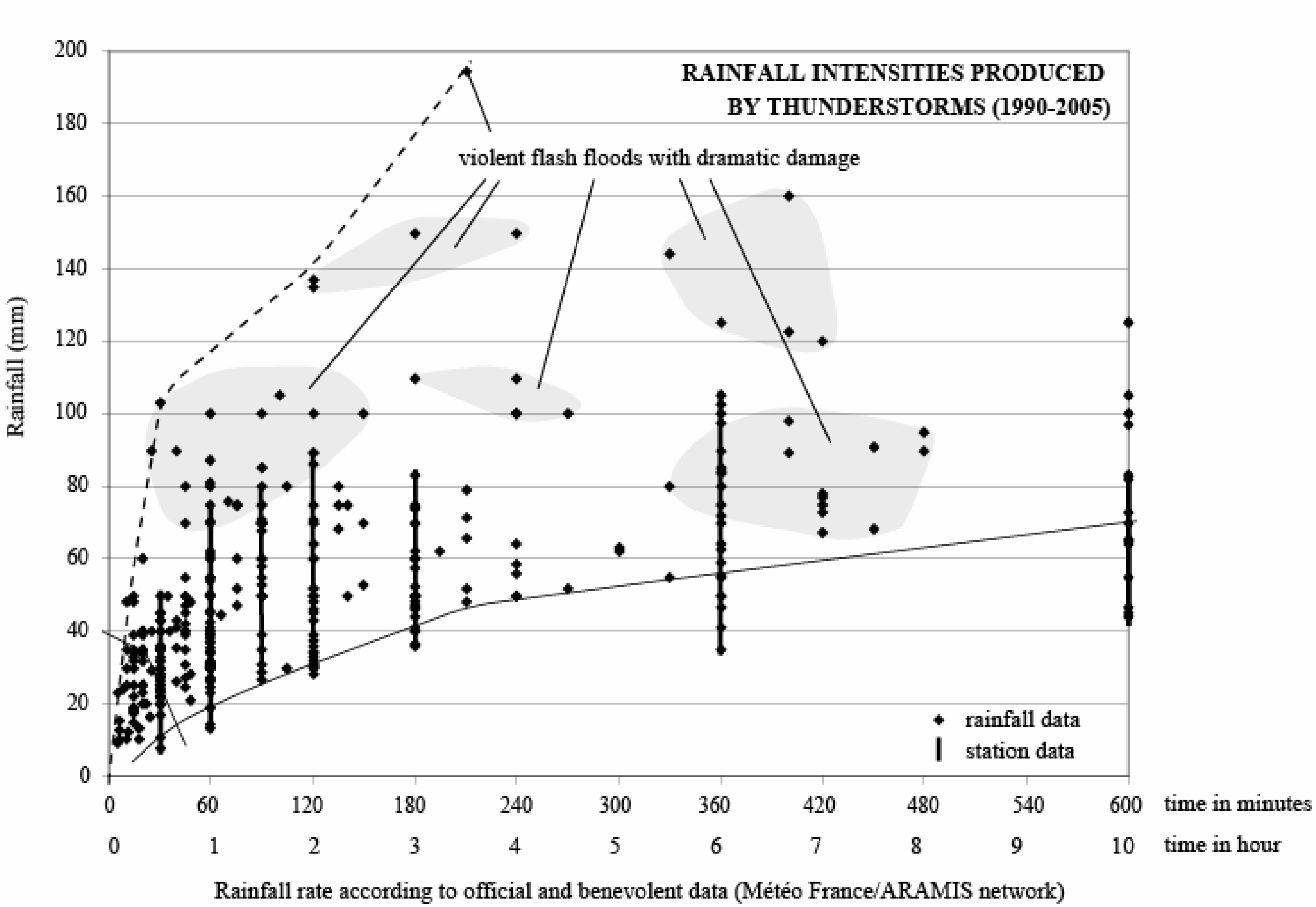
2. BACKGROUND

Terminology of hyper-concentrated floods

These floods present **single features** quite those different from others :

1) they are produced during spring or summer by paroxystic meteorological events concentrated both in time and space.
These **thunderstorms** provide **high rainfall intensities** (ranging to 35 from 200mm) which do not last for more than several hours.



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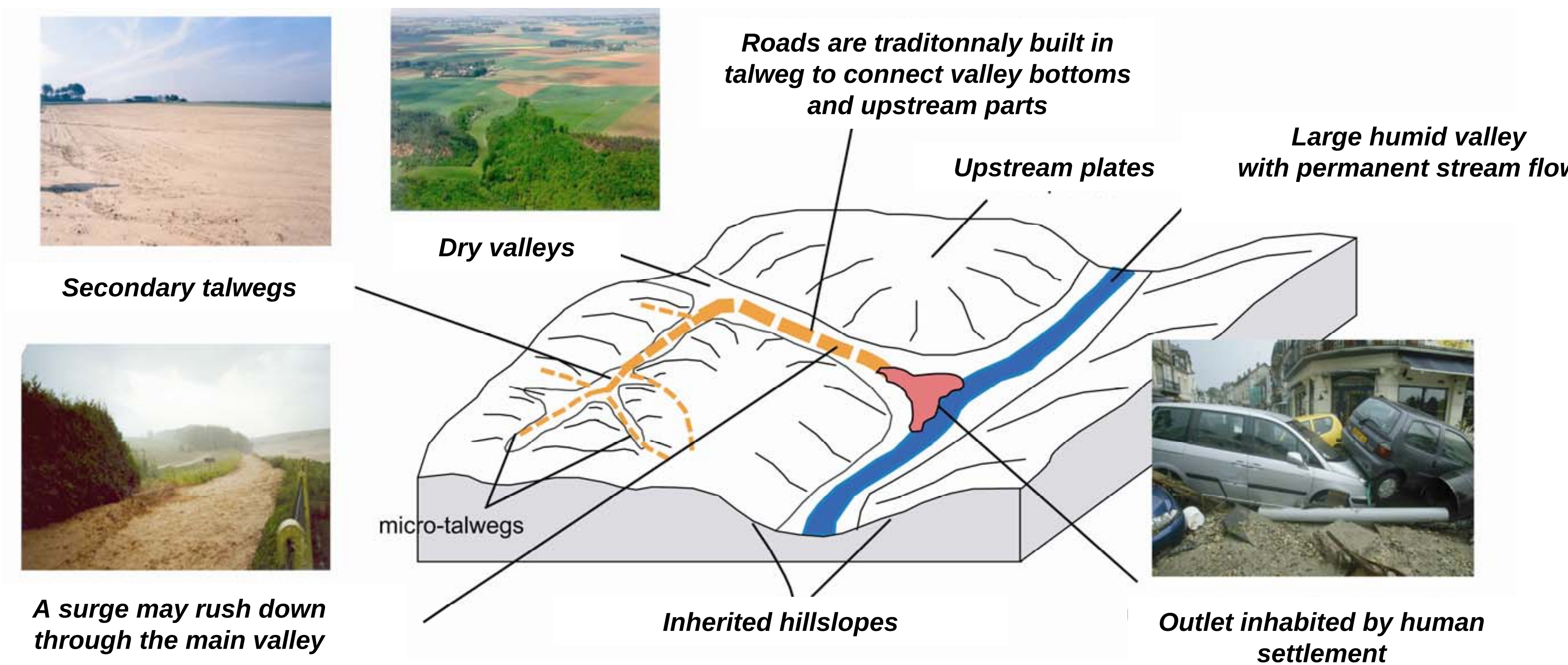
2. BACKGROUND

Terminology of hyper-concentrated floods

2) The **overland flow** is the dominant hydrological process. Infiltration excess is usually the unique alimentation source of runoff waters which have an extremely sudden onset. Runoff are produced on cultivated areas in upstream parts and currently involve a **sudden rising peak wave in dry valleys**. Dangerously, a surge may rush down the main valley just a few minutes after the peak of rainfall.



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2. BACKGROUND

Terminology of hyper-concentrated floods

3) As a consequence, as valley bottoms and outlets of dry valleys are inhabited by human settlement, **dramatic human and property damage** are regularly observed at the outlets.

incised roads

Important silt and blocs deposits (silex)

inundated houses

cars carried out

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3. PROBLEM STATEMENT

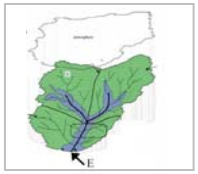
Why we choose Cellular Automata models ?

Dynamics of such type of floods remain **still seldom analyzed** for the following reasons:

1 The small dry valleys are **ungauged** and do not present permanent stream flow.

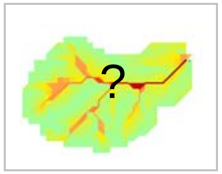
As hydrological data miss, simulating tools are needed to better understand these floods

2 A few research has focused on **the effects of the catchment morphology** because of the dominant weak-slope gradients and a temperate oceanic climate characterizing this area.



We want evaluating the influence of the spatial structures in this region.

3 Morphometric indices are **not useful for our study** because they describe the catchment morphology **in a planar dimension, in a static way**, and mainly they **never consider the dynamic effects of topography** on the surface hydrological processes.



The proposed methodology aims to simulate dynamical influence of morphology on surface processes using a CA approach.

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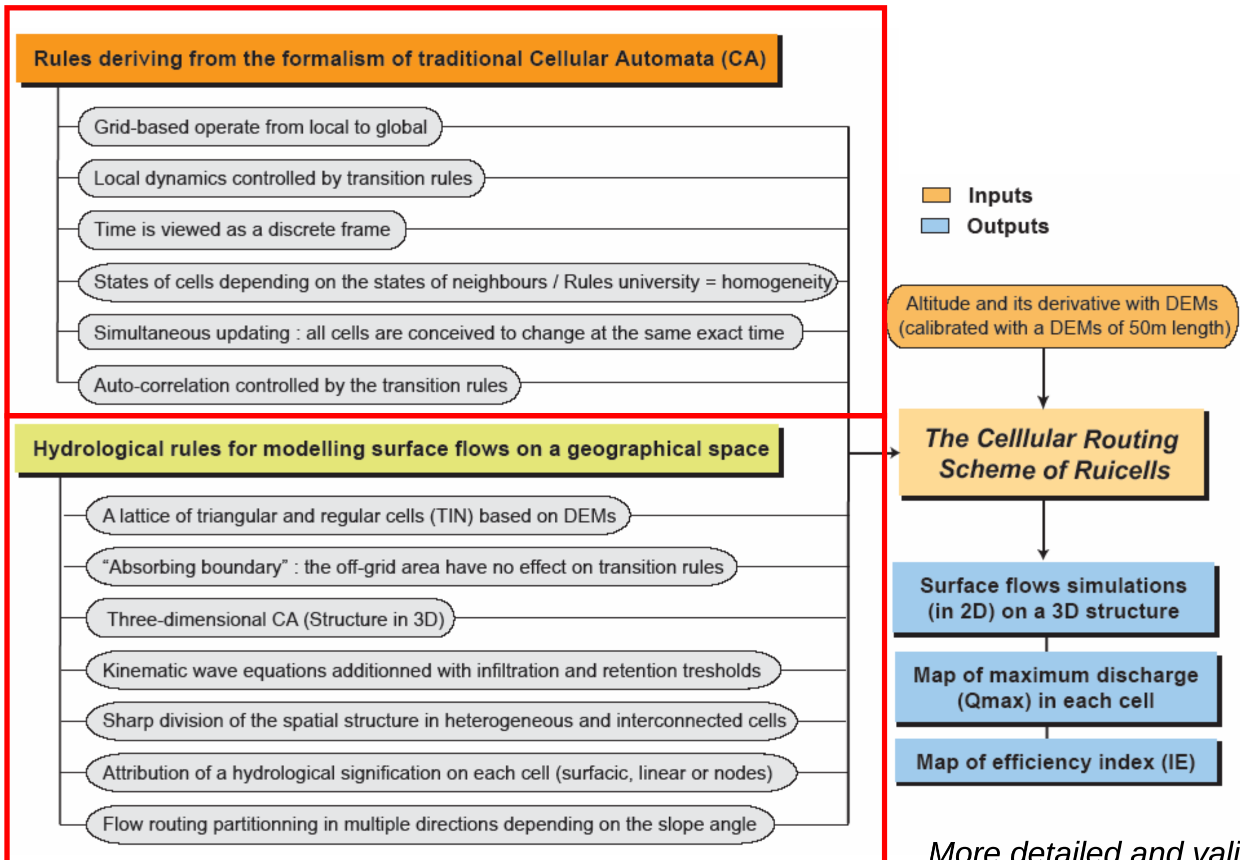
4. METHODOLOGY FRAMEWORK AND MODELING APPROACH

Use of RuiCells, *A Geographical Cellular Automata (GCA)*

Using a common language to others, our CA model was developed to find an **iterative method** to measure the influence of each morphological component on the surface flows at different scales.



"Ruicells" is a **Geographical Cellular Automata, a mixture of**

-the traditional CA formalism, in which **transition rules** dictate how the different cell states will react to state configurations present in the neighborhood of each cell (Von Neumann, 1951, Wolfram, 1983),

- the **multiple transformations** required for the **modelling of hydrological processes** on the geographic space (Depraetere et Moniod, 1992; Tarboton et al., 1997 for examples).

More detailed and validated in Delahaye and Langlois (2002) – Ruicells, outil de simulation dynamique – RIG 12 (4), pp. 461-487

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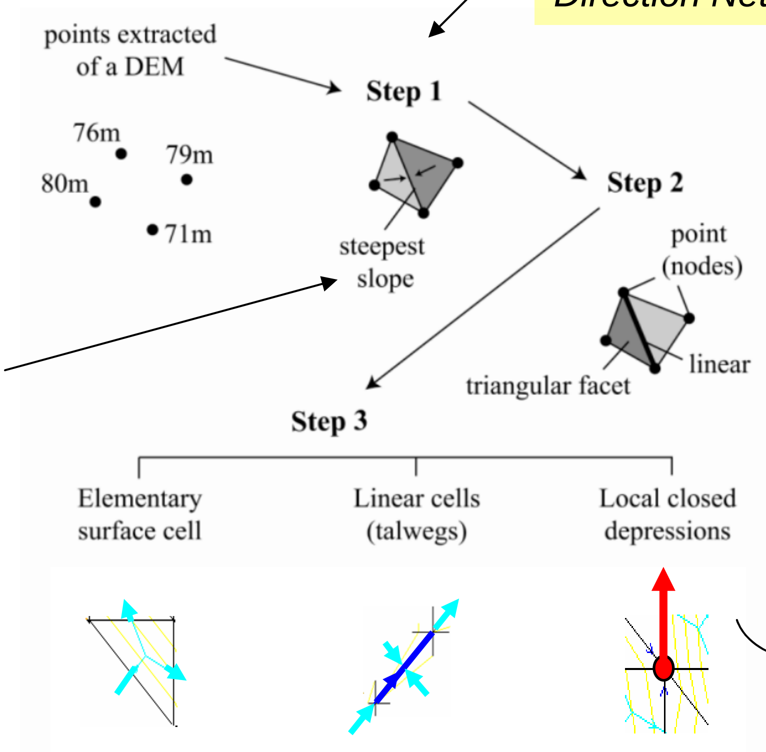
4. METHODOLOGY FRAMEWORK AND MODELING APPROACH

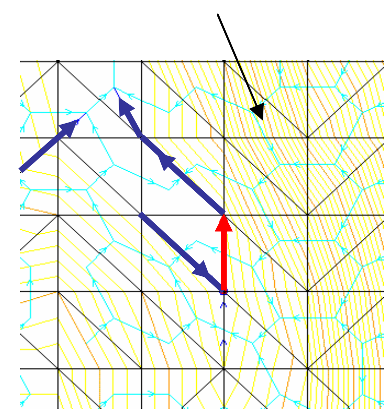
The structure of CA « RuiCells » : a lattice of triangular irregular surface cells

Step 1: *Creation of a* ***topological mesh*** *based on a DEM in triangular finite elements (like the Local Drain Direction Network used in PcRaster).*



Step 2: *Attribution of a* ***hydrological signification*** *on each cell* :
- surface cell
- linear cell
- local depression

Step 3: *Construction of the* ***flow graph*** *to form the cellular unit. Surface flow routing is proportionally partitioned in function of the slope angle.*



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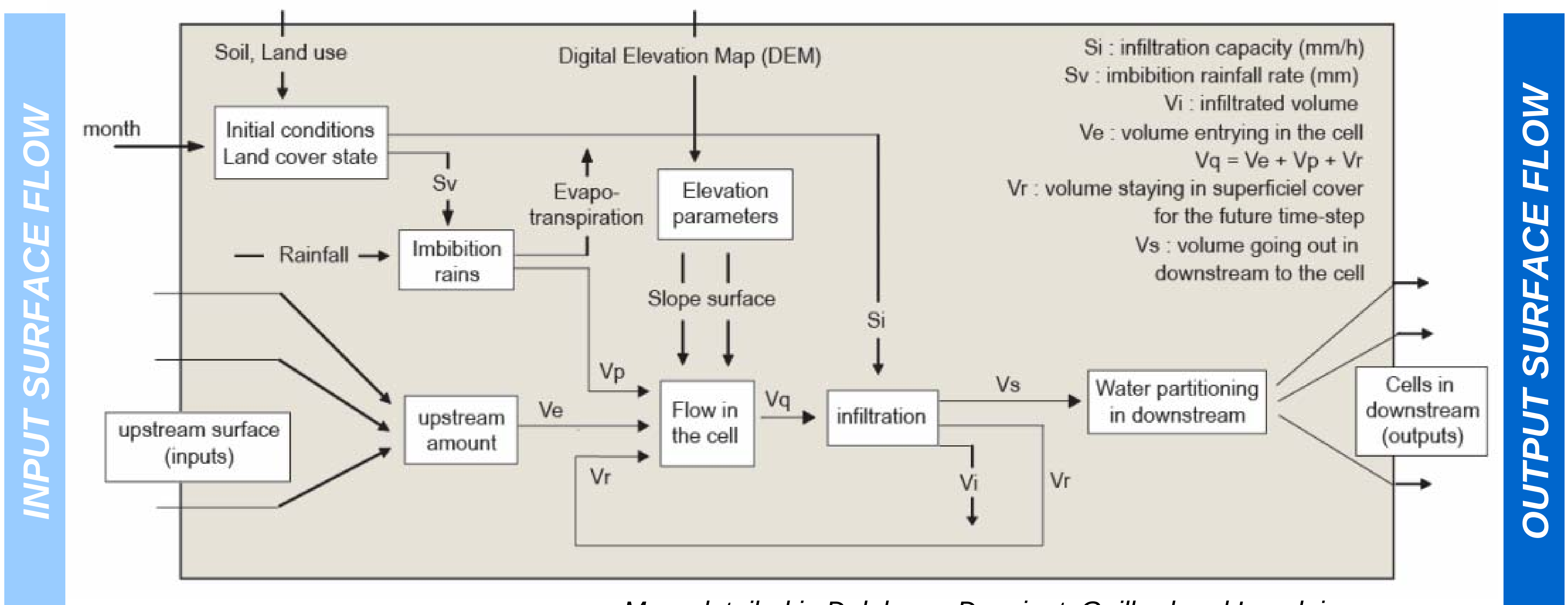
4. METHODOLOGY FRAMEWORK AND MODELING APPROACH

Parameters implemented at the cellular scale

In each cell, a hydrological model is implemented, controlling the **input** or **output surface flow.**
Surface flow simulations are uniquely presented in this study.

T n —— **One iteration (length-step defined by the DEM)** ——→ **T n + 1**



More detailed in Delahaye, Douvinet, Gaillard and Langlois (2007) European Geographical Union (EGU), Vienne (Poster).

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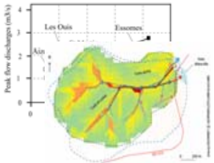


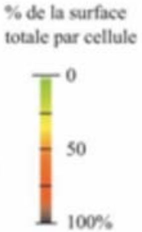
5. SIMULATION RESULTS AND EMERGENT PROPERTIES

Dynamical simulations of the surface flows at global scale

As the upstream surface is calculated on each cell during the simulation, **maps of surface flows** can be drawn, and inform on the way in which surfaces are connected together. Here, the slope is not implemented in the simulations. Simulated hydrographs show spatially surface flow response.

Villers-Ecalles (Seine Maritime)

St Martin de Boscherville (Seine Maritime)



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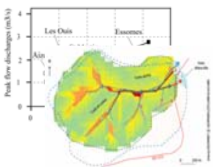


5. SIMULATION RESULTS AND EMERGENT PROPERTIES

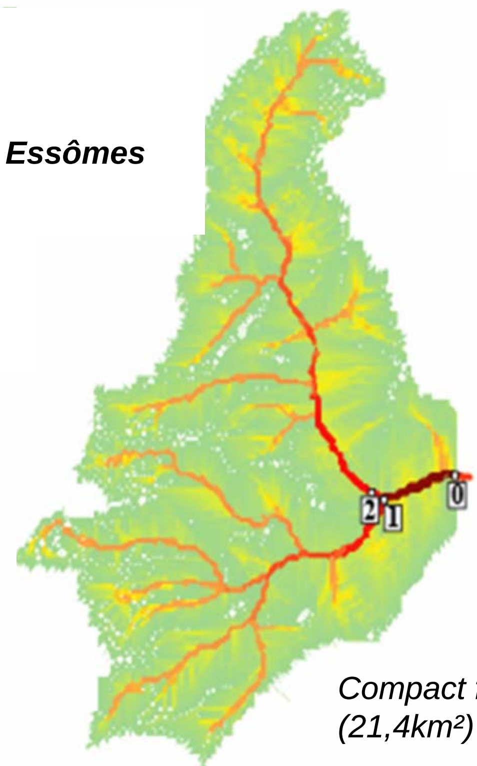
***FROM** Local and sub-catchments contributions **TO** Global response*

At the global scale, the catchment response express a **morphological signature,** but the global response have been broken up in order to identify the evolution of the peak of surface flows through local scales and since the upstream parts. Simulations show different behaviours and underline the effect of cascading system between surfaces :

Lézarde

Compact form
Hierarchical network
(13,4km²)

Essômes



Compact form
(21,4km²)

St Martin

Elongated form
Dispread network
(14,3km²)

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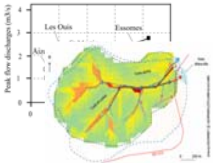

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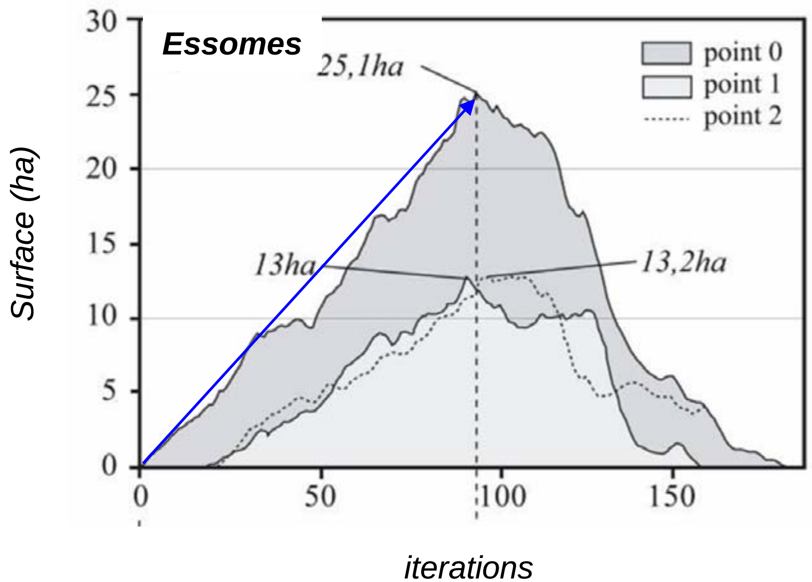
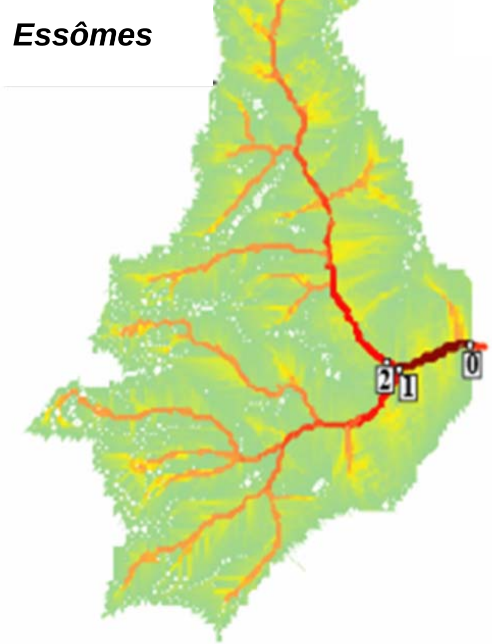
The peaks of the two main sub-catchments are approximately located at the same distance for the final outlet, and contribute together to the final peak flow.





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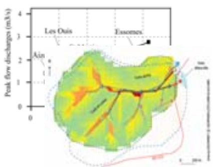

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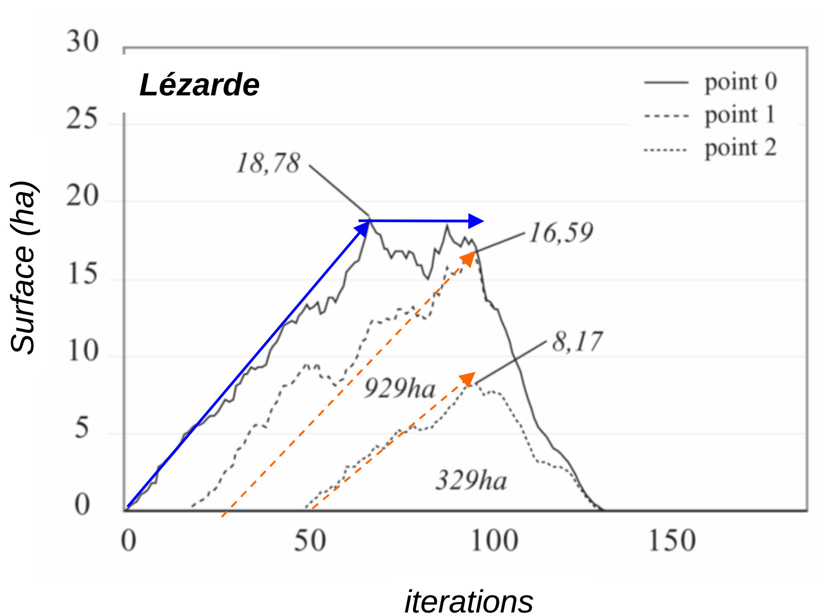
The similar contribution (1/3) of three sub-catchments explains the regular peak flow increasing on Lézarde. This catchment present an internal homothetic behaviour (Rodriguez-Iturbe and Rinaldo, 1997).



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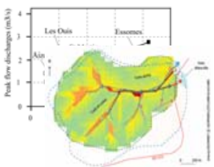

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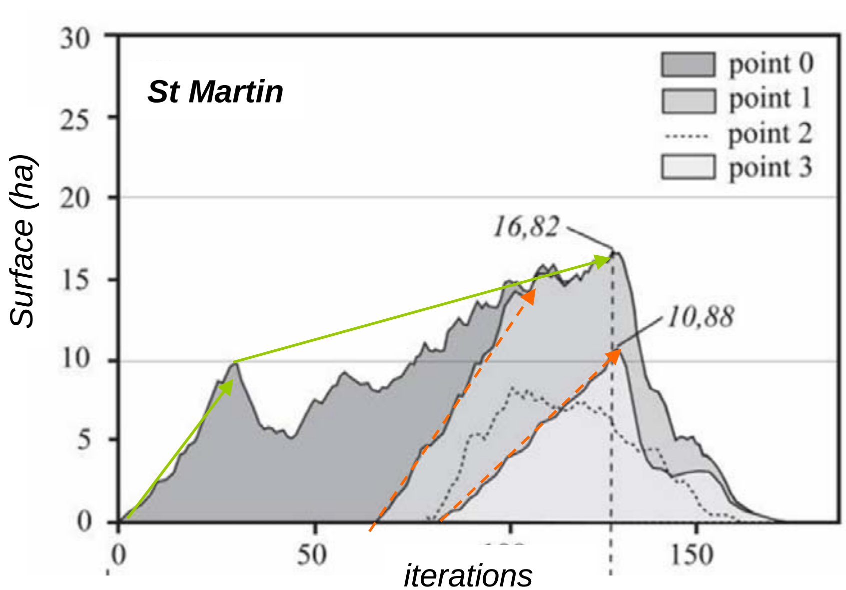
However, the cascading surface flows become inefficient and the flow-out longer when contributions of the sub-catchments are shifted for the outlet. And the spatial discrepancy induces such a long flow-out.



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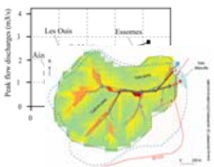


5. SIMULATION RESULTS AND EMERGENT PROPERTIES

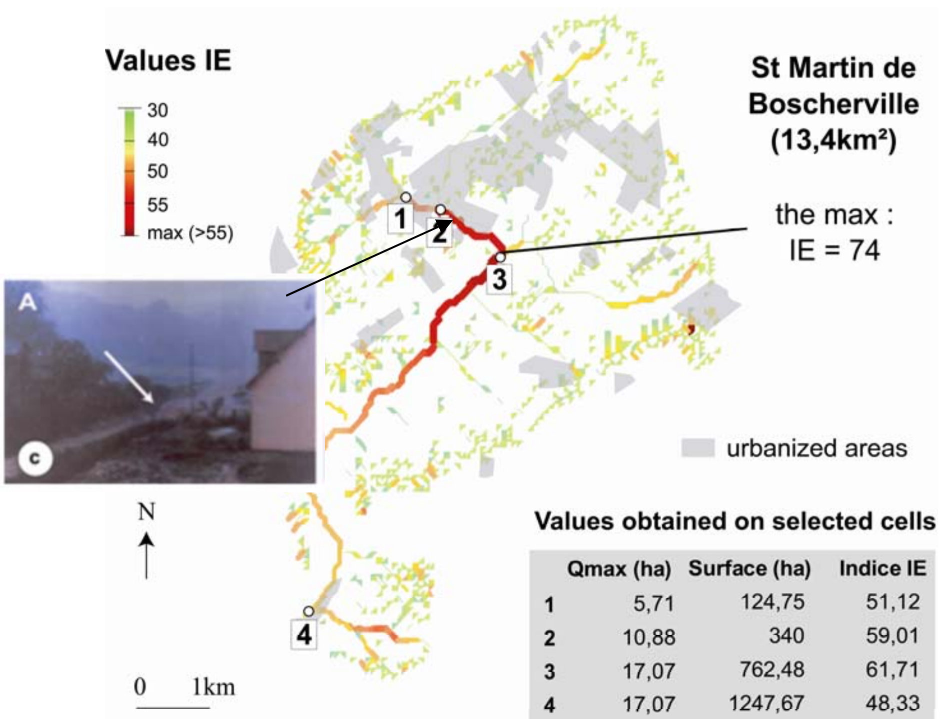
Identifying points of efficiency of the drainage network within the catchment shape

- We propose to calculate at the cellular scale an **efficiency index** defined as follow :

$$IE = \frac{Qmax}{\sqrt{A}} \times 100$$

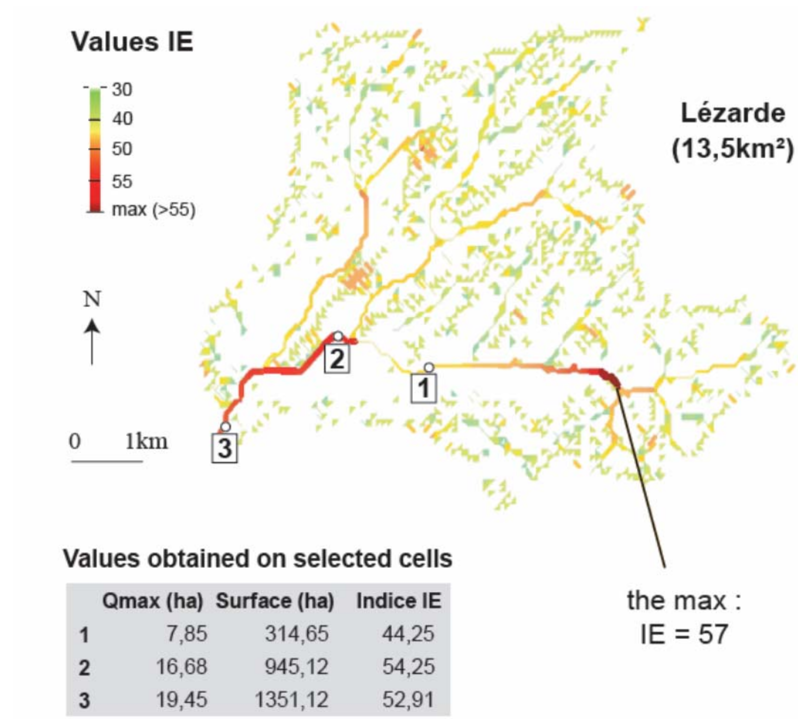
IE = Efficiency Index
Qmax = Peak of surface flow
A = Surface area

- Higher values suggest that the **maximum length of cells** located at the same distance from the oultet (defining *Qmax*) approaches the **average diameter** of a catchment (so a perfect circle). Such a indice identifies all the "**neuralgic points" in upstream of which the spatial structure Is strongly efficient**.



Values obtained on selected cells

	Qmax (ha)	Surface (ha)	Indice IE
1	5,71	124,75	51,12
2	10,88	340	59,01
3	17,07	762,48	61,71
4	17,07	1247,67	48,33



Values obtained on selected cells

	Qmax (ha)	Surface (ha)	Indice IE
1	7,85	314,65	44,25
2	16,68	945,12	54,25
3	19,45	1351,12	52,91

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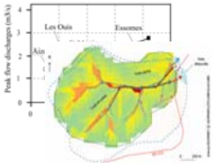
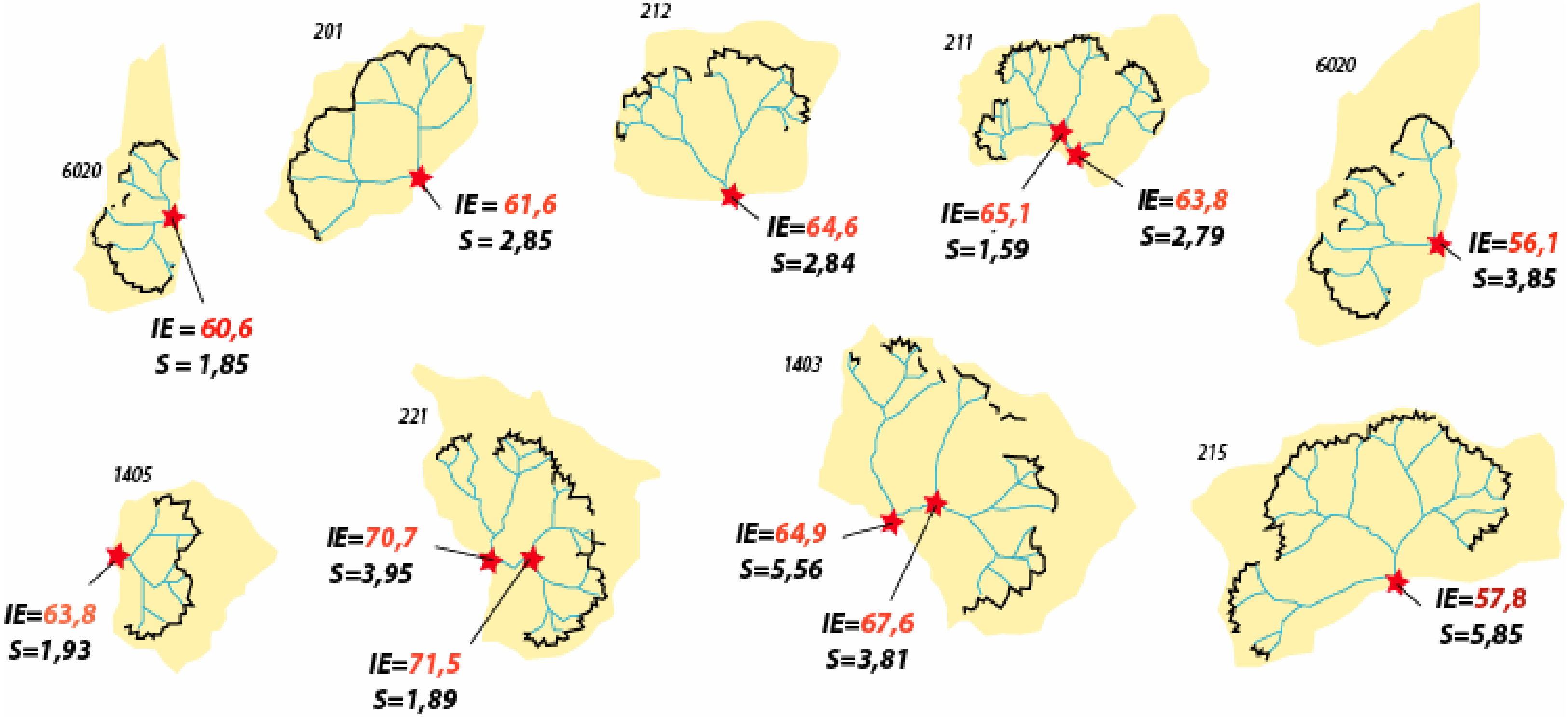


5. SIMULATION RESULTS AND EMERGENT PROPERTIES

Testing and evaluating efficiency of various drainage networks

- We can define, with the help of *RuiCells,* a **theoretical surfacic hydrological potential** at local scale and detect spatial configurations in which the network is the most efficient. We also have the same efficiency with different patterns (so *the same effects but not the same causes*…).
- Maps allow localizing **efficient points** while the global catchment scale can screen such potential.
- Such spatial configurations can became dangerous if rains are concentrated during a few hours.



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UN TORRENT DE BOUE
ET D'EAU DEVALE
SUR DAUBEUF

6. SUPPLIES AND DISCUSSIONS

Theoretical and methodological contributions

- In all points within a catchment, we can simulate its theoretical response.

- Results highlight that the structural organisation of the catchments, the local connections between surfaces and networks, and distance from outlet, explain the emergence of morphological signature at the global catchment scale.

- Maps of Efficiency index allows comparing theoretical hydrological potentiels for areas presenting different spatial configurations. This also show similar efficiency (the same effect) for various network patterns (different causes).

- While classical morphometric parameters are looking for scaling effects or power laws, this approach leads to track anomalies which determine original responses.

So, the concept of "catchment scale", classically used in hydrology, is not adapted for assessing such flash floods. The spatial structure is here more relevant !
We observe in all points of space "emergence processes" in hydrologic response.

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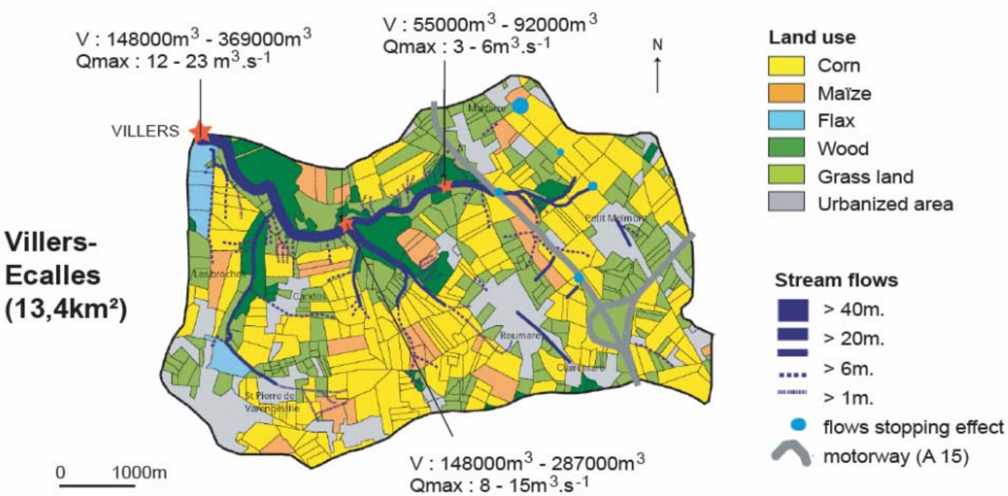
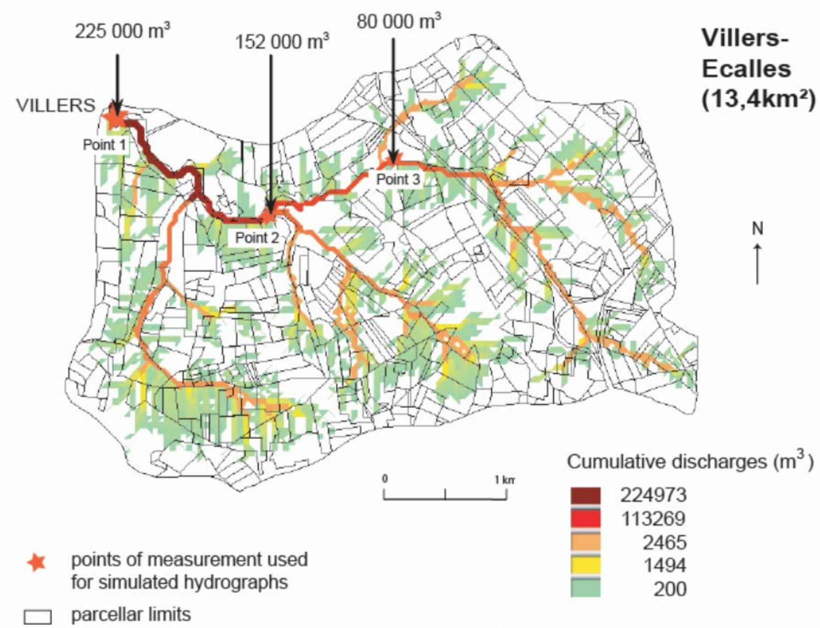
6. SUPPLIES AND DISCUSSIONS

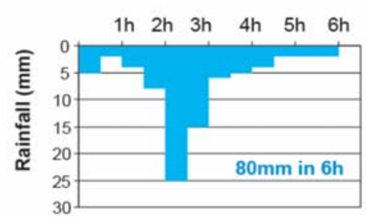
A simple tool for assessing flood risk

The CRS of *RuiCells* also leads to implement other parameters (land use, rainfall data, runoff coefficients, initial water content, urban areas… hedges, roads, burrows, *in development*). So additionning one to one other parameter, we can control the complexity of our model and mainly we can validate or not our research hypothesis.. It is fundamental in complex systems!!





Land use cover	Runoff coefficients
Corn	0.2
Maïze	0.4
Wood	0.05
Forest	0.05
Flax	0.2
Urban and roads	0.4



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Thank you for your attention !!

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