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Predicting potential flash flooding damage in a sedimentary context: Recent results obtained in Upper-Normandy (France)

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Abstract

This study proposes one original issue of having better knowledge on potential flash flood damage for territories and urbanized areas (houses, roads) in small dry valleys belong to sedimentary contexts. Such experimentation should improve actual prevention made at the global basin scale in the department of Seine-Maritime (in Upper-Normandy, France). Driven according to a set of three deterministic hydrological rules of flow pathways, the simulations proposed with the Cellular Automaton *RuiCells* permit us to assess the relations between the organization of networks and surfaces in a specific form. One Index of Concentration (IC) allows detecting confluences upstream of which networks and surfaces are well-organized in space and time. The correlation with declared damage, field experiments and local knowledge seems very relevant in five basins as the numerical simulations exhibit sites where flash floods induce important material or human damage and where further water concentration results in high-incised gullies. Leading such approach on many basins (180) in Seine-Maritime (Northern France), we notice that many IC with high values are not (fortunately) correlated to houses and human settlement. Therefore, several roads built in the main thalweg connect high surface flow concentration to urbanized areas located downstream. The latter becomes indirectly exposed to the flash flooding risk. All the maps realized on the 180 studied basins permit to detect 21 areas with high degree of sensitivity, on which field experiments and discussions with local actors are led at present. Such information should help risk managers to prevent possible damage in case of future flash floods.

Keywords: preventive maps, flash floods, numerical simulations.

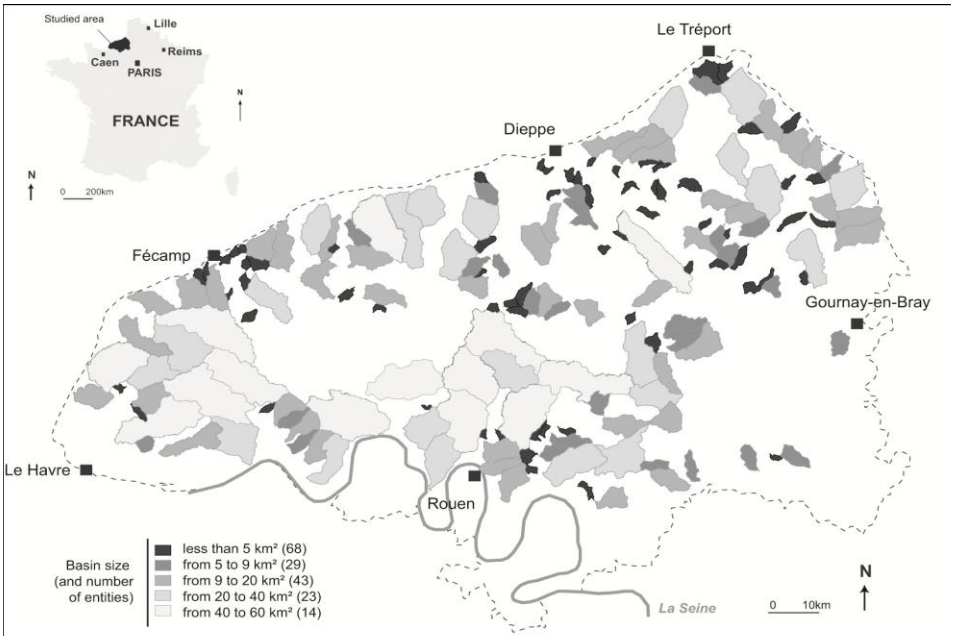
1 Introduction

Flash floods are common but poorly predictable phenomena [1, 2, 3]. Much of the uncertainty associated with these flash flooding events is due to a lack of accurate environmental data [4], to the variability of high rainfall intensities [5] and to the complex relations between topography, flow pathways, nature of land cover and soil properties [2, 6]. To address the gap in available information, many approaches have been proposed. Event-based and opportunistic investigations strongly enhance the information content [2]. Lightning meteorological data can provide details on the timing and location of convection in the storm environment [5]. But well-assessing the hydrological or physical processes still remain difficult for several reasons: i) river measurements and classical field-based experimentations are rarely collected in the basins of small size [7]; floods are insufficiently documented as they produce destructive effects [8]; iii) the rareness of these events makes the calibration of models and the statistical analysis delicate [9].

In this study, we focus on flash floods occurring in Northern France. They present single features quite different from those others [7, 8]. Stream flows are characterized by sub-torrential dynamics, with time-responses of less than one hour to high rainfalls (up to 50 mm in less than 15 hours), and by high sediment contents. Most of the flooded basins (< 40 km²) are small dry valleys where flows do not exist in normal period. The diffusive runoff rapidly shifts to concentrated runoff, generating high-incised gullies in a few meters. Erosive forms with a depth of several meters and a lateral extension exceeding ten meters are often observed in compact loamy soils, but major incisions generally appear at the outlet of basins of 1st or 2nd orders. The morphological component explains this paradox. Due to high-slope gradients and a rapid steep sidedness, runoff compensates the weakness of water amounts, while the thalwegs of basins of 3rd or 4th orders are quite more adapted to evacuate high discharges and lessen erosive capacity of stream flows. Estimations of a few specific discharges (ranging from 1 and 2 $m^3.s^{-1}.km^{-2}$) and of a few specific stream powers (from 22 to 511 W/m²) show that the highest values are related to the most important impacts.

If processes are clearly identified now, no predictive system exists at global or regional scales. At local scale, the CODAH (Communauté d'Aggloméation Havraise) is the only one to have its own alarm system on a basin of 80 km². On the other hand, municipalities can recently access to an Alert to High Rainfall Intensities created by Météo France since the 2011, 1st, January. But they cannot anticipate cumulative amounts of discharges or predict the locations of damage. Consequently, it becomes urgent for risk managers to possess few predictive maps where sensitive areas are identified, independently of all meteorological alerts. In our previous studies, we quantify the sensibility to flash flooding in 10 basins [10] in combining the potential surface flow concentration (linked to the flash flood hazards) with the spatial distribution of houses (and not others kinds of building) and roads (and not other networks such as train) to work only on resident population. Even if it should be interesting to consider other societal stakes, we assume that our definition of flooding risk is simplified. This paper present new results obtained on higher number of basins (180) located in Seine-Maritime (Upper-Normandy, North-western France). These basins present various sizes, topographies but all belong to the sedimentary Paris Basin (Figure 1). Our approach needs to be validated on an important number of basins if we expect to propose such maps in other sedimentary context.

Figure 1: Location of the 180 studied basins (Seine-Maritime, Upper-Normandy, in Northern France)



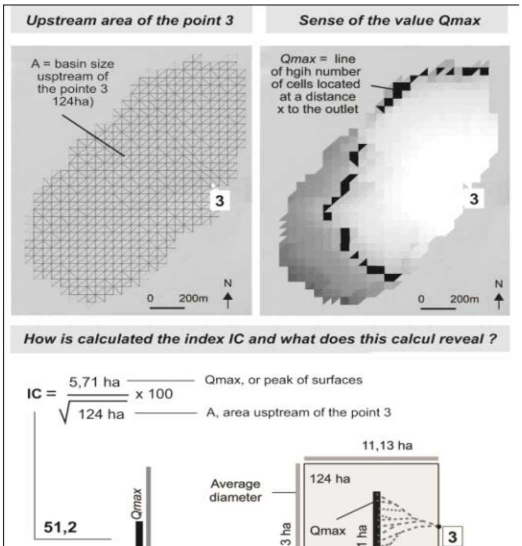
2 Material and data

2.1 Quantifying the surface flow concentration

In order to measure the surface flow concentration, a specific index has been created using numerical simulations obtained with the Cellular Automaton *RuiCells*. Structure, functionality and inputs or outputs data have been published before [11, 12]. The spatial mesh, based on a Digital Elevation Map, has been divided in triangular, interconnected or regular cells to better explore the effects of topography on surface pathways. At the beginning of the simulations, cells are initialized with their surface. Thus, surface moves simultaneously from cell to other downstream. Obtained at the outlet defined initially, a map permits us to follow the increasing surface flow-out [11]. A *surface flow graph* cumulates surfaces during iteration and this iterative process depends on the resolution of the DEM (of 50-meters here). Assuming simplified conditions regarding the flow routing [13] and runoff generating processes, these graphs may traduce the spatial behaviour of one area [14] and improve the *width function* formalized by Shreve, 1969 [15]. This latter calculated the number of links in the network with a flow distance *x* to the outlet, but our framework is not only based on links in networks. Our results also differ from those obtained with the *Link Frequency Distribution*, with the *Area-distance-function* where the distribution of pixels covering the drainage area is used [16]) or from those regarding the *surface flow travel time probability* distribution through networks [17] as time is not integrated during our iterative process. *RuiCells* improves previous methods thanks to deterministic rules and to the triangular mesh. It is also easier to assess organization of networks within a specific form (2D) or to add on it effects of slopes (in a 3D dimension). In this study we uniquely focus on morphological influences in the 2D-dimension.

To define the potential of surface flow concentration, we use the surface flow graph. The maximum peak of surfaces *Qmax*, corresponding to the higher line of cells located at the same distance from the outlet, is divided by the square root of the upstream area (Figure 2). We justify this division by the well-shown relation between maximum discharges and the square root of one basin [14]. We multiply the ratio by 100 to render the analysis easier: more Qmax equals to 100, more this value approaches the average diameter. In one example (figure 2), *Qmax* (5.7ha) is divided by the square root of the downstream area (124ha), giving one Index of Concentration (IC) of 51,2.

Figure 2: Creation and sense of the Index of Concentration.



Automatically calculated during the simulation process and then available in each cell, all these IC indexes present scalar dependence according to the resolution of the DEM initially used. A numerical model with a higher resolution gives lower values for the peak of discharge and also for this index. When we use a model of 50 m., all the indexes exceeding 50 indicate a medium surface flow concentration as it seems that the peak of surfaces represents more than half of the average diameter. If IC exceeds 55, it reveals that the networks and surfaces are well-structured with a minimal discrepancy of energy within the basin form. It confirms the existence of a Self Organized Network [18]. On the other hand, all the confluences upstream for which such concentration is observed are potential points of important and rapid concentration of surface flows. Adding effects of slope angle might provide a better evaluation of this potential but we uniquely focus on the links between surfaces and networks in two dimensions in this study.

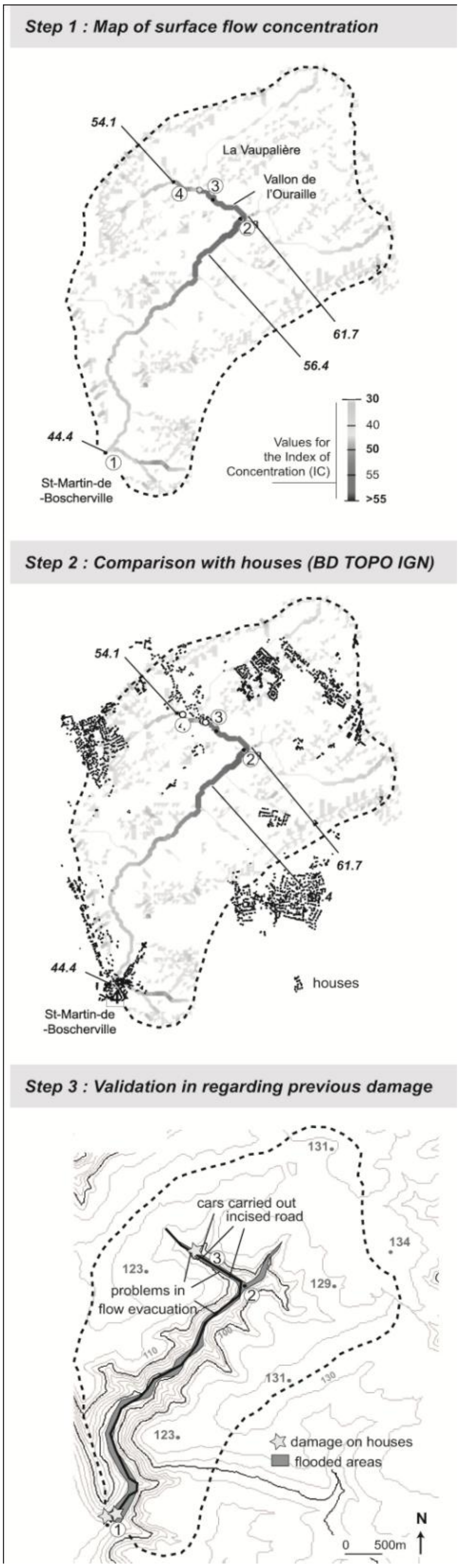
2.2 Comparison with houses and roads

This potential of surface flow concentration is compared with the spatial distribution of houses and roads at fine scales (with the BD TOPO © IGN 2007) to identify sensitive locations to flash flooding. In a first time, this approach has been validated on 13 basins where we observe a good correlation between the IC indexes (up to 55) and the damage registered after previous events [10]. On the basin of St-Martin (figure 3), cells with IC up to 60 are clearly similar to the most damaged cross-section: the main road was incised on a distance of 300 m with a depth of 2m.; several cars were carried out (and unfortunately, three persons died in the vallon of Ouraille); charring sediment and loamy content were found at the final outlet, routing on more than 2 km since the source area. Upstream houses located near the road and the surface flow concentrations present important sensitivity in this case. During the 1997, June 16th event, some inhabitants observed well a surge rushing the main thalweg in few seconds (figure 3). Financial costs due to this flash flood have been estimated to more than 5 M€ and attempt important value if we compare this value with the basin size (14km²).

Built for other 167 basins, these maps are discussed with the risk managers to validate or not the reality of these IC indexes (step 3 – validation). Many events occurred during the last decades and field experiments are not useful because flash flood marks disappeared. But good knowledge of local actors (problem in evacuation of water during events for example) or of population can improve this scientific method. Documents collected by mayor-elects, who have to prepare municipalities in advance in case of a future crisis due to flash floods, and historical sources constitute other useful data. At present, all the IC indexes are precisely studied and discussed (step 3).

On the other hand, these preventive maps appear simplified in comparison with the risk definition [19, 20, 21]. Indeed, our risk analysis is uniquely based on simplified hazard (potential of surface flow concentration) and on houses or roads (a small part of population vulnerability), without taking into account other management parameters. Knowledge on hazards has to be improved precisely, but we develop this predictive method at local scale because data or hydrological measurements are not sufficient. Hence, we assumed these data are simple but on the other hand, maps with this index are the only tool we possess to anticipate the future flash floods in these areas.

Figure 3: Three steps required to validate predictive maps – Results obtained on the basin of St-Martin.


Step 1 : Map of surface flow concentration

Step 2 : Comparison with houses (BD TOPO IGN)

Step 3 : Validation in regarding previous damage

Source: modified from Douvinet, 2012.

3 Results and discussions

3.1 Location of surface flow concentrations

High values for the IC indexes have been mapped at the intra-basin scales on the 180 studied areas. We register 119 points with IC up to 50 (60 indexes > 55 and 28 > 60) but also 102 lines where surface flow concentration remains on a distance up to 100 m (34 lines > 60). Numerical results are presented at regional scale to facilitate the comparison between basins. At this global level, 112 basins present at least one concentration up to 50 (figure 4). We mainly identify 76 morphological and functional areas (MFA), in keeping areas in upstream of high IC indexes (without depending on the global basin scale) but in erasing values less than 55. The synthetic map shows that the surface flow concentrations are not organized in space as closed basins can present high or low indexes. Therefore, the geological component explains this result: indeed, high values are observed in basins in evolution, in geomorphological term, especially in western part of one NW/SE directed fault which extends from Fécamp to Lillebonne. The south-western block groups numerous basins affected by previous flash floods in the last two decades (1983-2005), so we can link (again) these surface flow concentrations with potential damages. Such type of basins is also found along the Bresle valley, in eastern part. Without an increase of high rainfall and without variations in rainfall intensities on these basins, topography and geological components appear like the main dominant-controlling factors on flash flooding [6, 12]. In this department, these parameters predefine a number of areas ready to generate flash floods and the morphology plays again a key role at the intra-basin scale guilding the surface flow concentrations [8].

The other basins where IC indexes do not exceed 50 present elongated and non-compacted forms, non well-organized and non-hierarchical networks, and sub-basins are not connected in space. All these reasons strengthen the IC indexes and join results obtained with other approaches [12, 14].

Mapping the surface flow concentrations aims at traducing different spatial behaviors. If basins are well-organized, these IC indexes should be present at the final outlet, but this idea is not proven here: only 11 basins (on 180 studied areas) present such concentration (with medium IC, ranging from 55 to 60). On the other hand, most of the basins (49) present one or more internal surface flow concentrations and in this case the global basin scale does not have any hydrological pertinence in case of flash floods. For these basins, risk managers need to survey upstream areas, mainly if they are cultivated as they aggravate velocity of surface flow-out and the sudden rising peak waves.

Other basins have original behaviors. 7 basins are strongly organized as the surface flow concentrations remain higher (up to 55) through scales; they present a homothetic behavior [14]. *Qmax* and upstream areas irregularly render increasing the IC indexes since local to final outlets. Concentrations become also more efficient at the final scale in 5 basins as IC never decreases between confluences of sub-basins. The other studied areas present high IC indexes punctually located (19 basins) or in short-distance (21 areas). These concentrations do not have important effects on the global spatial structure and they are frequently observed along secondary thalwegs.

All these maps finally convey non-linear relations between surface and networks, and confirm that the global scale is not the best level required to analyze sensitivity to flash flooding hazards. After these first results, we compare the distribution of housed or roads to the main IC indexes, in order to improve sensitive locations taking into account resident population.

Figure 4: Location of higher IC indexes (up to 50) in the 180 studied areas (Seine-Maritime, France)

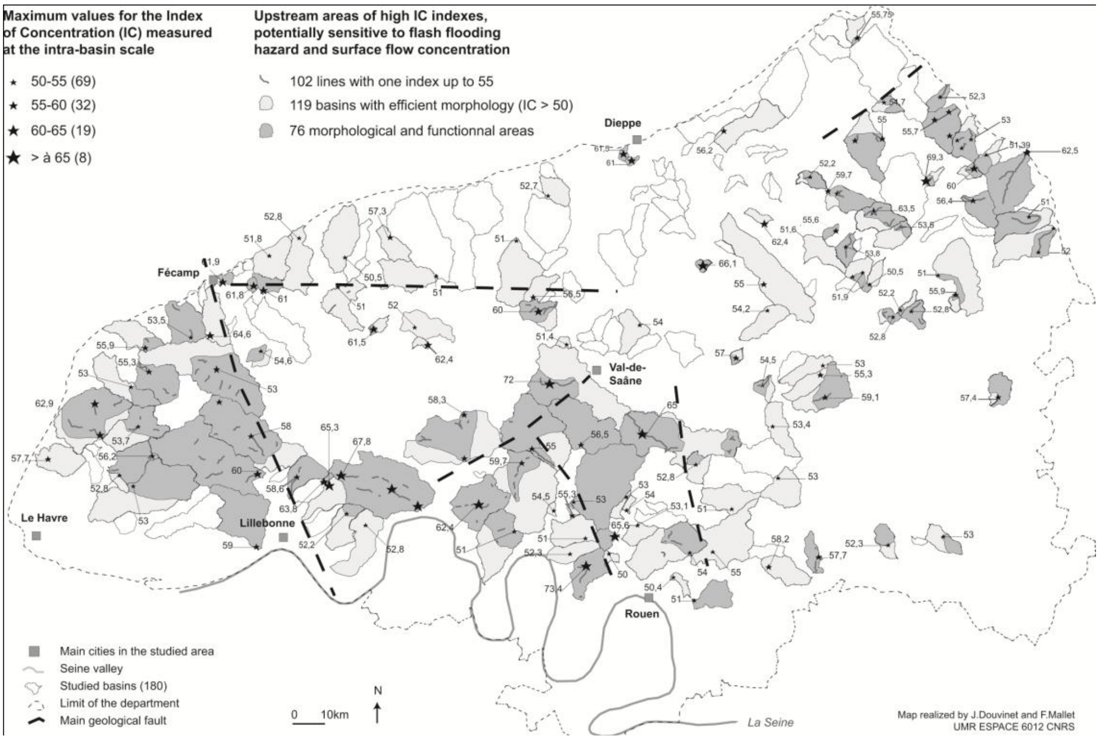
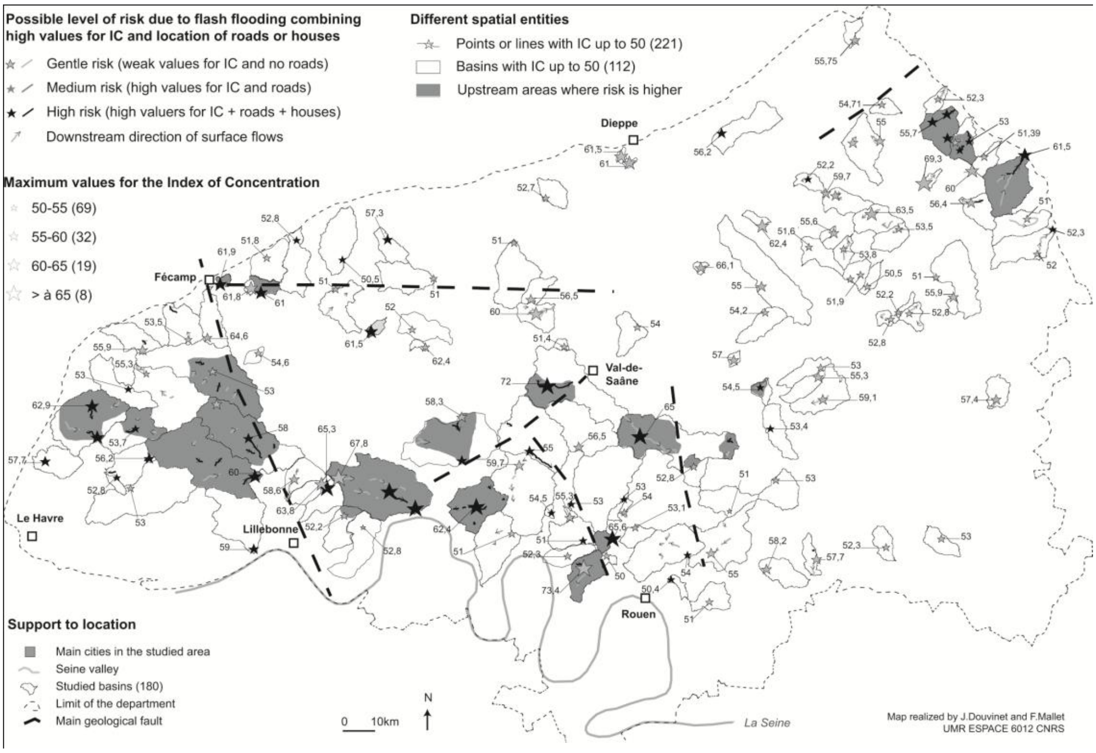


Figure 5: Combining roads or urbanized areas to high IC indexes to define possible sensitivity to flash flooding



3.2 Urbanized areas and sensitive locations

The location of roads and houses has been combined with the lines and points characterized by a surface flow concentration up to 50 (figure 5). Three colors have been discussed to define this flash flooding sensitivity: green (when risk doesn't exist), pink (risk on roads) and purple (risk on houses and roads). We map these results at the regional scale to detect all the points where societies can attempt problems. Initial colors have been converted in gray colors according to publication constraints.

Within the 112 basins presenting at least one index IC up to 55, we can define three groups: 39 basins where population or roads are not exposed to surface flow concentrations (34%); 40 basins where roads are sensitive (17 basins have gentle IC indexes while 10 basins present IC up to 60); 33 basins with a real risk of damage in case of flash flooding on roads and on human settlement (14 basins present IC less than 55 whereas 11 basins have IC up to 60). On the 40 areas with medium risk (roads are exposed), 26 have already been affected by events, and financial costs on road infrastructures were expensive. In these basins, risk can become higher on mobile persons as the latter run on roads without being aware of the possible flash flooding risk. Hence, there is a disconnection between sources areas and urbanized surfaces, but roads make the link between hazard and societies indirectly exposed. On the 11 basins with high risk and IC up to 60, damage were dramatic on 7 areas as 11 persons died on the period 1983-2005. According to these results, these simplified maps present a good correlation with reality, and can serve predictions on future risk in these areas.

Linking all the previous results we finally identify 10 + 11 = 21 basins where one IC (up to 60) exists on roads or urbanized areas. These basins locate in the SW of the department and along the Bresle Valley (in the NE). Basins with medium risk are in the west and north-eastern part, whereas gentle risk is in the central part and north. In case of high rainfall prediction, now we can anticipate the possible location where flash floods might be dangerous. If we want to improve such predictive maps, other information is needed: the estimation of probable costs for societies, the return period of high rainfall intensities over the most sensitive basins, etc. Once the relation between damage and the 45 IC > 55 is proven, such predictive maps method could also be coupled with meteorological alerts.

4 Conclusion

Linking the potential of surface flow concentrations with the location of roads or urbanized areas improve actual prediction to face to flash flood risk in the department of Seine-Maritime (France).This study permits to select 21 sensitive areas on the 180 initially studied basins, and on this, 15 basins have been effectively affected by previous flash floods. Such numerical simulations have now to be validated on more basins (the 112 efficient morphology basins) and for this some discussions are actually led with stakeholders, risk managers, mayor-elects or local population. If this approach seems to be well-adapted for many basins, we really expect to use it in other sedimentary contexts, as in the Nord-Pas-de-Calais or in Alsace in France, but also (why not?) in Sussex (U.K.), Wallonia (Belgium) or in China (loess plates) as these areas are generally affected by severe and dramatic flash floods.

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