Answers to anonymous Referee #1

General comments:
This paper deals with a very interesting and challanging issue: how to forecast the impacts of flash flood (FF)? Indeed, usually, flood forecasting related papers only deal separately with one issue: meteorology, hydrology, social sciences. This paper pro poses a common framework and presents a FF forecasting impact method, based on a 2-step chain: 1/ pre-determination of flooded areas allowing to define "potential" impacts and 2/ a real-time rainfall runoff model used to choose the relevent predetermined flooded area. This two-step approach is convincing. It is simple enough to be run in real-time. On the other hand, the needed simplifications (for instance in the hydraulic model) are carefully identified and analyzed on very well documented two case studies. Finally a "validation" is presented, based on insurance claim data. Considering the high quality of this paper, I would recommend its publication with only a minor revision.

My main suggestions (detailed in the following remarks) are:
- Some details in the methodology need to be better explained;
- I am not sure that we could talk about "validation based on insurance claim data" as
stated in the title, since as it is well explained in the paper, the ratio "nb of claim"/ "nb
of flooded policy" does not reach 100% and need here to be event-based calculated
using observation data (see my last remarks).

We thank referee n°1 for the careful reading and globally positive appreciation of our manuscript, and for having raised these two main weaknesses. We explain hereafter how we plan to address these important points (see our answers to detailed comments).

Detailed comments
1. Page 3, Line 19: reference not suitable : this authors are talking about the FFG, which is typically dedicated to ungauged catchment. Find some references dealing only with gauged systems.

OK, we propose here to keep these references but to reformulate the presentation of flash flood guidances, which are to our knowledge among the first approaches really devoted to flash flood warning: "The first approaches developed, namely the flash flood guidances, were based on a preliminary analysis of rainfall volumes generating bankfull flow, for several durations and catchment initial moisture conditions (Georgakakos, 2006; Norbiato et al., 2008). More recent approaches aimed to directly forecast peak discharges at ungauged locations based on distributed hydrological models and radar based quantitative precipitation estimates or nowcasts (… ".

2. Page 3, Line 20: Figure 1 and text are not totally coherent. The text mention 3 steps and the figure has 4 illustrations. After reading, it seems that illustrations a and b are related to step one and illustration c and d are relatated to step 3. Step 2 is not illustrated (1-D longitudinal water profil computation). I would suggest to make clearly appear the 3 steps on the figure.
3. Page 3, Line 23: Too few information is provided for step 3. How exactly do you move from the 1D longitudinal model to a 2D representation of the flooded area? Furthermore, from the Fig1 legend, it is understood that a (manual?) post treatment is applied to remove some disconnected area, not clearly mentioned in the text.

Actually figures 1.a to 1.c correspond to the three computation steps mentioned in section 2.1 (l.20-23), and figure 1.d to the additional post-treatments described in section 2.2 (p.4 l.21-24 and l.32-33). We suggest here to group the description of all these treatments in section 2.1 (see answer to point 4 below), and to reformulate the text for an explicit reference to the appropriate figure for

each step described. The caption of figure 1 will also be changed for an explicit reference to the computation steps described in the text.

4. Page 4, Line 13: maybe detail and regroup here all the manual corrections (including the removal of disconnected area if it is manually done, (see previous rq), in order to insist on problem of using an 100% automated method, and on the consequent amount of work you have done to deal with this issue in order to obtain coherent inundation areas.

Ok the description of additional treatments (corresponding to figure 1.d), will be moved from section 2.2 and grouped here (i.e. at the end of section 2.1). We will also mention here that these additional treatments could be applied automatically (even if it was done manually here).

5. Page 4, Line 15: The mentioned return periods are not coherent with the Fig2: 6 return periods on a), 10 on b). Furthermore, in the text, latter you also mentioned 10 flooded areas (page 5, line 18). I imagine the 10 return periods you analyzed are those of fig2b ie : 2, 5, 10, 20, 30, 50, 100, 300 (not 200), 200, 1000)?

The 10 return periods are indeed the following: 2,5,10,20,30,50,100,300,500,1000. The list in the text has therefore to be corrected. Figure 2.a includes only one part of these computation results: the T=30, 300, 500, and 1000 years maps are not included. We propose to modify this figure: see the joint updated version including a comprehensive representation of the results.

6. Page 4, Line 15: Do you have just a upstream flow input or also lateral flow inputs? If yes, how this lateral input is estimated and injected in the hydraulic model?

Only an upstream flow input was applied here for the computations, since the information on discharge quantiles was available only at these input nodes. Therefore the discharge is assumed to be homogeneous on each river reach. A comment on this important simplification will added in the text. Fortunately, the considered river reaches are not very long (~2 km in average) and the effects of this simplification should be limited. However, if necessary, running the hydraulic computations with lateral inputs would be possible based on a continuous discharge quantiles information along the stream network.

7. Page 4, Line 17: Which limit condition do you apply at the very last downstream reach ? How do you determine the length of each reach?

The limits of each river reach are determined by the output points of the rainfall-runoff model (which correspond here to the outlets of the french watershed database provided by the SCHAPI): this information will be added in the text (with a reference to sections 3.1 and 3.2 providing information on the lengths of the considered reaches). The dowsnstream boundary condition corresponds to the normal depth for a uniform flow regime: this will also be mentioned in the text.

8. Page 4 Lines 21-24: this point maybe need to be explained more explicitely (gives some partial answer to my rq 3).

See above the answers to remarks 3 and 4: this explanation on additional post-treatments will be detailed and moved to the end of section 2.1, with further comments on the possibility of automatization of these treatments.

9. Page 4 section 2.2: It seems to me that this section focuses more on the limits of the method than on the "catalogue of flood maps" as indicated by the title. I would change the name of this section to clearly indicates that you focus on the limits of the automated procedure presented in 2.1. I would also regroup in this section all the content related to manual procedures earlier mentioned in section 2.1. In this case, lines 15-19 should be put in 2.1. or maybe in 2.3 which is a little too short in comparison with the other sections. (nota: this change in your plan is only a suggestion)

Our proposal is to reorganize the plan in the following way (by grouping sections 2.2 and 2.3):
2.1 Simplified automatic implementation of 1-D steady-state hydraulic models

10. Page 5 Line 18: "10 flooded" area ? see rq 5.
10 flood maps are actually used for the computation of the impacts models. See answer to remark 5.

11. Page 6 Line 3-4: what spatial and temporal resolution were finally adopted for the rainfall-runoff model in your case studies ? (maybe to be mentioned later, but I didn t find the info in the rest of the paper)
Some elements on the spatial resolution (5km² elementary catchment area for the definition of river network integrated in the model) are provided in section 3 but are probably not sufficient. The temporal resolution of the computations is 15 min. A sentence will be added here to detail these aspects.

12. Page 6 Line 6: If I understood, the "reaches" and cross sections defined here are not the same that in the previous section. How are they determined? Are those mentioned in table 1?
The river reaches considered in the hydraulic computations and in the rainfall runoff model are identical: this will be mentioned by adding a sentence on the model resolution (see previous point). However, the geometrical characteristics of the cross sections are simplified and assumed to be rectangular in the rainfall-runoff model, since only the flood wave transit time has to be well anticipated (see next remark for the determination of the cross sections widths).

13. Page 6 Line 13: "the width of river reaches is the main parameter controlling the transfer function and is estimated based on the Strahler order of river reaches" but previously you wrote Line 6 : "The width of the cross-section varies with return period of the discharge". Could you please clarify exactly how widths are calculated (same rq as 12)
The widths are estimated based on a generic formula proposed by Versini (2010): $W=Lo.i^2$, where i is the Strahler order and Lo is an elementary width having 3 different possible values depending the discharge return period. These details are provided in the cited reference (Naulin, 2013), and are not crucial here in our opinion. Therefore we propose to remove the sentence on line 6 and to reformulate line 13 :"the width of the river reaches is the main parameter controlling the transfer function and is estimated based on the Strahler order and discharge return period (for further details see Naulin et al., 2013)"

14. Page 8 Line 17: temporal and spatial resolution?
1 km² of spatial resolution, 5 min of temporal resolution in both cases. However, this does not correspond to the resolutions of rainfall runoff computations (see above).

15. Page 8 Line 20: may be change the title by:Reference flood maps obtained from previous studies"
(just a suggestion)
OK, we agree.

16. Page 10, Line 7: There is a jump in the figures numbers. Maybe renumber the figure 7 in figure 4.
OK, this will be done.

17. Page 10, Line 32: "It was worse testing if it could provide a number of private houses affected by the floods for each river reach to be compared to the outputs of the proposed forecasting chain." Worth instead of worse? Please reformulate. What do you exactly mean?
We propose a simplification of this sentence: "We tested herein if it could provide a number of private houses affected by the floods to be compared to …"

18. Page 11 Line 12: do you know how hydrometric services extrapolate these rating curves? Using hydraulic consideration?

The extrapolation may be based either on a local hydraulic modelling (Alès and Mialet) or on an expert-analysis of hydraulic control of the streamgauge section (Banne). These important precisions will be added in the text.

19. Page 11 Line 32: replace 'form" by "from"

OK.

20. Page 12 Line 21: "This explain why..." Please explain why.

We propose this reformulation "It is important to note that the low-flows water heights are limited in these Mediterranean rivers. This explains why bathymetric data is not crucial to obtain a relevant estimation of the cross sections shapes: aerial topographic surveys are often sufficient to get an accurate representation of the river beds in Mediterranean regions."

21. Page 13 Line 31: How is your rainfall-runoff model initialized (in particular the initial soil moisture conditions)? Don t you think that can also be a (important) source a uncertainty?

Indeed the initialization of the rainfall runoff model is a crucial aspect which can result in significant bias in the estimation of peak discharges. The model initialization is performed here based on the initial method proposed by USDA, using the 5 days antecedent rainfall: this will be mentioned in section 2.4 with a reference to Naulin (2013) for details. More generally, the rainfall-runoff simulation represents a significant part of the final uncertainty of the whole simulation chain. This is illustrated by figures 5.b and 5.d, and commented in section 4.3.

22. Page 13 Line 31: "forecasted peak value" => Maybe replace "forecasted peak value" by "simulated peak value" in all the text since, the RR model is run in a "simulation" not a "forecasting" mode (using QPE, not QPF).

OK, this will be done.

23. Page 14 line 2: In figure 6 legend replace TSI by ISR

OK.

24. Page 14 line 12: maybe change "forecasted peak by "simulated peak".

OK.

25. Page 14 line 26:"Clearly, the number [...] has a random component". I agree, but your random binomial process take into account 'all' the errors of the damage database.

We propose here to modify the sentence: "Clearly, the number of reported claims per river reach has a random component due both to the claims triggering processes and to the limits of the claim database."

26. Page 14 line 29: Maybe indicate explicitly that you choose p=0.37 and p=0.43 from table 2, so knowing the number of "observed" claim divided by the number of policies effectively flooded (ie using the observed flooded area). Do I correctly understand? Or do you divide by the number of policy flooded according to your model (ie using the modelled flooded area)? In this last case, it is not a validation since p seems to me a kind of last adjustment parameter which unbiased the impact model. Please clarify.

Yes, the ratios should be computed inside the actually observed flood area, and without using the computed flood areas. However, the observed flood area may not be available everywhere. By default, our proposal here is to compute the C/P ratios on the 1000-year flood extent (which differs from the simulated flood area for the considered events). This may lead to slightly underestimate the C/P ratios since some non-flooded areas are incorporated in the estimation of the ratio. A sentence will be added in the text to clarify this point.

27. Figure 8: But I maybe missed one point. Why can we see some "horizontal" steps into the claim/policies relation (blue). How did you exactly plot these blue curves?

The binomial process correspond to a discrete random variable: each realization c of the variable is necessarily an integer (c being the number of claims reported for one river reach). The non-exceedance probabilities $F(c)$ increase by steps in function of c and cannot be exactly equal to 0.05, 0.50, or 0.95. For this reason, the intervals limits were computed here as the lowest discrete c values for which $F(c)>\alpha$, $\alpha \in (0.05,0.50,0.95)$. This explains the steps in the curves especially when the number of claims is limited. To avoid this, we propose to estimate the intervals limits by linear interpolation between c and c-1, with $F(c-1)< \alpha< F(c)$, $\alpha \in (0.05,0.50,0.95)$. We join the updated figures.

28. Page 15 line 4-5: I don't understand. I thought you used the 'observed' flooded area to calculate the total number of policy (see rq 26). Please clarify.

Provided that the observed flood area is not available everywhere, our choice was again here to estimate the reference number of claims based on the 1000-year flood envelop (i.e. without using the simulated flood area, see answer to remark 26). This time, this choice may result in a significant overestimation of the number of claims observed in the actual flood area.

29. Page 16: I globally agree with the conclusion. But does your paper also suggest that this insurance data are not suitable for a 'real' validation of the impacts (if you mean that "impact" = "nb of claim"), since you need to know the ratio "number of claim"/ "number of impacted policy"... Maybe further researches are also needed in this direction?
How to better estimate this ratio (by removing the other errors you mentioned from the database)? And then how to "forecast" it (is there some national coherences?)?

Clearly the validation process could still be improved. First, by a better identification of claims really related to river flooding in the claim database, which is unfortunately out of reach at this time. A predictive estimation of the claim ratios would also certainly enhance the validation process. Such estimations are usually obtained by insurance companies based on mean relations between claims ratios and inundation water levels, generally established at a large scale. Therefore, a further research step could be to use the water levels from our 1-D hydraulic computations to directly estimate the claim ratios. This consideration will be added in the conclusion.

Answers to anonymous Referee #2

General comments:
The idea presented in this paper is interesting and potentially very useful. The paper is well structured and well written. The authors present a novel procedure aimed at computing a series of flood extent maps on a dense stream network and directly evaluating the possible associated impacts. The proposed approach consists of an integrated forecasting chain that combines a one-dimensional simplified hydraulic model and a distributed rainfall-runoff model for the simulation of discharges over the stream networks, and it has been tested on insurance claim data. Potential limitations and critical issues in the implementation of the proposed methodology are also well documented and discussed throughout the paper. In my opinion, this paper can be considered for publication in the present form, after some minor points will be taken into account. Two main issues and some minor comments are listed below.

At first we would like to thank the referee n°2 for this positive appraisal of our manuscript, and for the detailed comments and suggestions provided. Our answers are detailed below.

1. In section 2, the automatic implementation of 1-D hydraulic models is described; however, the description of the third step is too short and should be completed with additional information. Moreover, from figure 1 it seems that four steps (a-b) are required for obtaining the final map of flooded areas, that is not clear from the text. Finally, the choice of a fixed roughness coefficient is mentioned: a suitable reference should be inserted here. How is this value computed? And what are the possible consequences of keeping it fixed?

This remark is close to another one formulated by referee n°1. Actually figure 1 illustrates both the three computation steps mentioned in section 2.1 (p.3 l.20-23), and the additional post-treatments described in section 2.2 (p.4 l.21-24 and l.32-33). We propose to group the description of all these treatments in section 2.1 and to reformulate the text for an explicit reference to the appropriate figures. In the same time the description of the third step (p3 l.23) will be detailed as follows:" the estimated water levels are interpolated between successive cross sections and compared to the DTM elevations to compute the flood extent and water depth maps (figure 1.c) ".

The roughness coefficient was fixed according Lumbroso et al. (2012) who showed the necessity to limit the roughness values to keep reasonable values of flow velocities. This reference will be added.

The consequence may be a systematic overestimation of the water levels. But according to the results obtained in section 4, it seems it is not the case here.

2. If I understood well, the application of the method exclusively focuses on the flood peak as the variable of interest. However, it should be stressed that other variables (like, e.g., the flood volume and the flood duration) may play a significant role to the study of extreme flood events, and that the dependence among such variables can seriously influences the estimates of flood magnitudes (see, e.g., Salvadori, G., De Michele, C., and Durante, F.: On the return period and design in a multivariate framework, Hydrol. Earth Syst. Sci., 15, 3293-3305, 2011).

Indeed the flood duration and volume may largely influence the flood extents, particularly in the case of large rivers with wide floodplains. These variables could be accounted for by using synthetic hydrographs and unsteady hydraulic computations. However this procedure would largely increase the computation times, and would require comparing the reference synthetic hydrographs to the actually simulated ones for the application of the whole simulation chain. In the particular context of flash floods (very fast evolution and limited lead times), we considered here it was preferable to simplify the procedure, through the assumption that the flood extent is mainly influenced by the peak discharge. This enables to conduct the hydraulic computations in steady-state regime. This assumption is clearly presented as ones of the limits of the procedure (see section 2.2, p.5 l.10). It

nevertheless remains reasonable in our opinion since we are here working on small upstream watersheds, in relatively hilly areas. A comment will be added in section 2.2 about the reasons for this choice.

Minor comments
- Page 5 - lines 16-17: You mentioned 10 flooded areas, but I could not find them in figure 2.a. Please also check the return periods reported on the x-axis in figure 2.b which differ from the one mentioned at the beginning of section 2.2.
Yes indeed the text includes here an error and has to be corrected. The 10 return periods used are actually the following: 2,5,10,20,30,50,100,300,500,1000. Figure 2.a presents only one part of the computation results. An updated version is proposed (see joint file) including all computed flood extents.

- Page 6 - lines 23-24: Here, it may be appropriate to clarify that "the continuous discharge-impacts relations" are the continuous curves obtained by linear interpolation that express the relations between discharge return periods and number of impacted insurance policies.
Yes the relations are obtained by linear interpolation. We propose here to add a reference to section 2.3 and figure 2 which provide details on this important methodological aspect.

- Page 8 - line 8: "September" and "June".
Ok this will be corrected (page 11 line 8).

- Page 8 - line 15: I suggest to specify here that the rating curves are graphs of discharge versus stage for a given point on a stream, and maybe add a comment on how such curves are extrapolated in your work.
The extrapolation may be based either on a local hydraulic modelling (Mialet and Alès) or on an expert-analysis of the hydraulic control of the streamgauge section (Banne). This precision will be added in section 4.1.

- Page 10 - lines 32-33: The sentence "It was worse testing if it could provide a number of private houses affected by the floods for each river reach to be compared to the outputs of the proposed forecasting chain" is not clear. Please, reformulate.
We propose a simplification of this sentence: "We tested herein if it could provide a number of private houses affected by the floods to be compared to …"

- Page 12 - lines 7: replace "figure 4d" by "figure 4.d". Please check the crossreferences throughout the paper.
OK, to be corrected.

- Page 12 - line 33: A synthetic incoherent surface ratio is here introduced. I suggest to add a comment on such quantity and/or an appropriate reference.
We propose to add the following comment: "A synthetic incoherent surface ratio (ISR) is computed (eq. 1). It represents the extent of excess and default surfaces, expressed as a proportion of the reference surface".

- Page 13 - lines 22-23-24: Remove the space before the semicolon.
OK.

- Please check the punctuation of the figures' captions.

OK.

Answers to anonymous Referee #3

MAJOR COMMENTS

The present article shows a novel methodology for the estimation of the flash flood impacts using a hydraulic model and a rainfall-runoff model. The article is well written and structured which makes it very understandable. The figures are pretty illustrative and are well explained in the text. Some methodology aspects must be better explained in the text since it is a relevant section for this article and some processes are not mentioned in depth (rating curves, river reaches, better explanation of the models operation, etc). The validation of the impact model with insurance data gives an extra and innovative point in the article, showing the importance of this data and all the information it can provide. From my point of view, this article is ready for publication, with some minor changes:

We thank referee n°3 for this detailed review of our manuscript. The suggestions formulated largely meet the remarks from the two other referees. We detail hereafter our answers to each of these specific points:

SPECIFIC REMARKS

1. Page 3, Line 28: consider using the same punctuation throughout the text. For instance, dots for decimal numbers (n=0.05). I suggest to add some reference explaining why it is used this specific roughness coefficient.

This lack of reference was also pointed by referee n°2. Actually the roughness coefficient was fixed according to Lumbroso et al. (2012) who showed the necessity to limit the roughness values to keep reasonable values of flow velocities. This reference will be added.

2. Page 4, Line 33: take care with the citation of the figures, it is different throughout the text (i.e. figure 1.d instead of figure 1d).

Ok, this will be checked and corrected as necessary.

3. Consider using always the same English spelling (UK or US). For example, in the Figure 2, the word "catalog" is used, however in the text is used "catalogue". The same with the words "modelled" and "modeled".

Ok, we will be check this and adopt the same English.

4. Why "km2" are the only units that are in italics? I suggest putting all them in the same way.

Ok, we agree all units should be typed in the same way, this will be done.

5. Page 7, Line 12: in this section (3.1) the meaning of "river reach" is explained for the first time. Consider explaining it before.

We propose to move this explanation to the introduction section, since the term river reach is used in this section for the first time.

6. Page 8, Line 2: "altimetric" instead of "altmetric".

Ok, this will be corrected.

7. Page 9, Line 19: it is said in the text that is only used private houses, mostly individual houses (>7m height). What about public or commercial buildings? Does the CCR cover them?

Public buildings are only partly covered, and commercial buildings are generally covered. However we decided to exclude this information, since the addresses of insurance policies often do not correspond to the location of the insured buildings in these cases. Therefore the real location of the damaged buildings cannot be determined accurately.

8. Write the meaning of all the acronyms appearing in the text for the first time. For example IGN RE (page 8, line 1) or QPEs (page 8, line 17)

Ok the meanings will be added at the first apparition.

9. Consider citing internet sites, instead of including the wrl in the text.

The URLs of the different institutions will be moved in the acknowledgements sections.

10. Please change the order of the Table 2, since it is mentioned before Figures 4 and 5. The same case with Figure 7, it can't be mentioned in the text before Figures 4, 5, and 6.

OK the order of tables and figures will be modified to better follow the citations in the text.

11. Consider including more information about the rivers of the case studies, like the average discharge and the maximum peak discharge of both flood events in one of the stream gauges shown in the figure 3.

We propose to add some peak discharge values estimated for both events at several points of the considered river networks. However, since almost all the stations were damaged during the floods, the information on mean discharges is not available.

12. Figure 6: "ISR" instead of "TSI". Which modelled value is used for the ISR estimation? The upper or the lower bound? Why the ISR values are estimated just in one of the case studies (Draguignan 2010)?

OK the acronym will be replaced. The lower bounds have been used for the computation of the ISR values (this will be mentioned). The ISR values are presented on one case study to preserve the readability of the other figures showing the comparison between observed and simulated flood maps (lower and upper bound). We propose to keep this, since the ISR ratios computed on the other case study do not show significantly different features.

13. Page 10, line 32: I don't understand the sentence "It was worse testing if it could provide a number of private houses affected by the floods for each river reach to be compared to the outputs of the proposed forecasting chain".

All the referees pointed out the necessary reformulation of this sentence. It will be replaced by: "We tested herein if it could provide a number of private houses affected by the floods to be compared to …"

14. Page 13, line 5 and 7: "ISR" instead of "IRS".

OK. This will be corrected.

15. Page 15, last paragraph: Figure 9 is wrong mentioned in the text.

OK. This will be modified.

16. References: change the order of "Gourley et al." references, since the newest one must be placed after the oldest one.

OK. This will be done.

17. Figures:

- Use always the same units, "km" instead of "kms" (International System)

- Take care with the punctuation of the decimal numbers of the figures.

- The position of the "a); b); c); d)" within the figures must be always the same. Change it in the Figure 1.

- All the captions must have the same format

OK. This will be done.

The challenge of forecasting impacts of flash floods: test of a simplified hydraulic approach and validation based on insurance claim data

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Abstract. Up to now, flash flood monitoring and forecasting systems, based on rainfall radar measurements and distributed rainfall-runoff models, generally aimed at estimating flood magnitudes - typically discharges or return periods - at selected river cross-sections. The approach presented here goes one step ahead by proposing an integrated forecasting chain for the direct assessment of flash flood possible impacts on inhabited areas (number of buildings at risk in the presented case studies). The proposed approach includes, in addition to a distributed rainfall-runoff model, an automatic hydraulic method suited for the computation of flood extent maps on a dense river network and over large territories. The resulting catalogue of flood extent maps is then combined with land use data to build a flood impact curve for each considered river reach: i.e. number of inundated buildings versus discharge. Theses curves are finally used to compute estimated impacts based on forecasted discharges. The approach has been extensively tested in the regions of Alès and Draguignan, located in the South of France, where well documented major flash floods recently occurred. The article presents two types of validation results. First, the automatically computed flood extent maps and corresponding water levels are tested against rating curves at available river gauging stations as well as against local reference or observed flood extent maps. Second, a rich and comprehensive insurance claim database is used to evaluate the relevance of the estimated impacts for some recent major floods.

1 Introduction

Hydro-meteorological forecasts are essential for an efficient real-time flood management, especially when the situation is evolving rapidly. Forecasts provide crucial information to ~~crisis~~ emergency managers for the anticipation and appraisal of the forthcoming floods that may affect areas at risk. In the particular case of flash floods, often affecting simultaneously a large number of small ungauged streams, suitable forecasting systems are still currently under development over the world. The first ~~proposed methods were focused at gauged stream sections, where rainfall-runoff models could be calibrated (Georgakakos, 2006; Norbiato et al., 200~~ ~~, leaving a large part of the potentially affected stream network uncovered.The most recent developments aimed at providing forecasts also at ungauged locations . These forecasts rely~~ approaches developed, namely the flash flood guidances, were based

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on a preliminary analysis of rainfall volumes generating bankfull flow, for several durations and catchment initial moisture conditions (Georgakakos, 2006; Norbiato et al., 2008). More recent approaches aimed to directly forecast peak discharges at ungauged locations based on highly distributed hydrological models and on radar based quantitative precipitation estimates (QPEs) or nowcasts (Cole and Moore, 2009; Rozalis et al., 2010; Wang et al., 2011; Javelle et al., 2014; Gourley et al., 2014; Naulin et al., 2013; Versini et al., 2014; Gourley et al., 2017). Such models provide indications of possible flood magnitudes, but are still rarely designed to directly evaluate the possible associated impacts. A large number of simultaneous alarms may be generated in case of a significant rainfall event by such highly distributed flash flood forecasting systems. And it is now recognized that end-users, such as emergency managers, who have little time for situation analysis and decision making during flash floods, crucially need rapid assessment of the possible field consequences and damage severity (Schroeder et al., 2016; Cole et al., 2016). Moreover, a direct forecast of possible field consequences opens the possibility for assessing the performance of flash flood forecasting systems in ungauged areas, based on reported consequences, as surrogate for measured flood discharges (Versini et al., 2010a; Naulin et al., 2013; Javelle et al., 2014; Moncoulon et al., 2014; Saint-Martin et al., 2016; Le Bihan et al., 2016). In the near future, real-time assimilation of proxy data for flood magnitude such as information contained in reports of rescue services or social networks could be envisaged. This article presents a proposal of such an integrated flash flood impact forecasting chain and illustrates its validation against insurance claims. If successful, such an approach may be of great help for both crisis emergency managers to better appraise the expected flash flood impacts, and for hydrologists to improve their modeling modelling approaches in ungauged situations.

Translating discharges into local possible impacts requires an estimation of the corresponding flood extent, as well as the knowledge of the level of exposure (location) of the considered assets and possibly of the vulnerability of these assets. This information may be difficult to assess and incorporate at the large scale at which flash flood forecasting systems are implemented to monitor a large number of small river reaches streams. Large-scale flood mapping approaches based on digital terrain models (DTM) were recently proposed and tested (Yamazaki et al., 2011; Pappenberger et al., 2012; Sampson et al., 2015). These works may offer an interesting way for an automatic treatment of DTM and flood mapping. But they were not designed up to now for the simulation of a large range of flood magnitudes and were generally applied at relatively large spatial resolutions: computation square grids from 100 metres up to 1 kilometre. Such resolutions are not suited to the representation of floodplains of small streams. On the other hand, detailed flood inundation mapping approaches are available at higher resolutions (Bradbrook et al., 2005; Sanders, 2007; Nguyen et al., 2015), but require large computational resources which limit the implementation possibility at a large scale. In both cases, most of the proposed mapping approaches would not be compatible with an application in real time.

The approach proposed hereafter combines an applicability at a large scale (computational efficiency), the possibility to be integrated in a real-time forecasting chain and a high spatial resolution for an appropriate representation of floodplains of small ungauged streams. It is proposed to compute automatically (i.e. without manual corrections) a series of flood extent maps for each river reach (a river reach being defined as the portion of river located between two confluences), covering a large spectrum of discharge values (i.e. discharge return period values). A DTM treatment method is proposed for the extraction of river cross-sections, that are used in one-dimensional (1D) steady-state hydraulic numerical models for the computation of water stages and

flood extent maps. Land use databases are then analysed to compute the number of buildings in the estimated flooded areas for each discharge value and each river reach. Based on this preliminary analysis, a relation between the discharge and the number of affected buildings is adjusted at the river reach scale and is then used as impact model of an integrated rainfall-runoff-impact simulation chain.

5   Even if the proposed procedure may appear relatively straightforward, the main challenge lies in its automatic application and validation over extended territories on a dense stream network - typically streams with upstream watershed areas larger than 5 ~~km^2~~ km^2. The validation is an essential step which should reveal if such a forecasting chain is able to provide reasonably accurate results, despite the necessary simplifications of such large scale applications (standard roughness coefficient values, 1D steady-state hydraulic models, missing bathymetric data,..), and sources of uncertainty (DTM accuracy, unknown 10   vulnerabilities,..).

This article presents the proposed method and its application on two well-documented test case studies. Two types of evaluations are conducted. First, the automatically computed flood maps and corresponding water levels are tested against the rating curves at river gauging stations as well as against local reference or observed flood maps. Second, a rich and comprehensive insurance claim database provided by the main French reinsurance company (Caisse Centrale de ~~Ré~~Réassurance) is used to 15   evaluate the relevance of the estimated impacts (number of possibly inundated buildings) for some recent major floods. The article is organized as follows: the first section presents the methodology developed for both, the implementation of the impacts model, including the computation of a catalogue of flood extent maps, and for the implementation of the rainfall-runoff-impacts simulation chain; section 3 presents the two application case studies and the datasets used for the validation; section 4 exposes and discusses the obtained results.

20 **2   The proposed rainfall-runoff-impact simulation chain**

2.1   Simplified automatic implementation of 1-D steady-state hydraulic models

The Cartino method (Pons et al., 2014), has recently been proposed to automatically build the input files and run one-dimensional (1-D) hydraulic models based on data extracted from high resolution Digital Terrain Models (DTM). This method has been used and adapted herein to derive catalogues of flood extent maps for a wide range of discharge values. The software 25   proceeds in three steps (~~f~~ Figure 1). First, the locations of the cross-sections are selected (Figure 1.a) and their shapes extracted from the DTM ~~.~~(Figure 1.b). Second, the corresponding input files are built and the selected 1-D hydraulic model is run to compute longitudinal water level profiles corresponding to each selected discharge value (Figure 1.b): the Mascaret 1D model (Goutal et al., 2012) has been used in the present case study. Third, ~~a post-treatment intersects the water level profiles and~~ the ~~DTM~~ estimated water levels are interpolated between successive cross sections and compared to the DTM elevations to 30   compute the flood extent and water depth maps (Figure 1.c).

~~To ensure an automatic computation, important simplifications are introduced in the structure of the hydraulic model: cross-section shapes are estimated based on a simple extraction from the available DTM, without additional information on topography or bathymetry; specific sections such as weirs or bridges are not represented; a unique roughness coefficient is~~

3

The first two steps are run in an iterative way to adjust the width of the cross-sections and their inter-distances for each

5   considered discharge value. The cross-sections should be wide enough to contain the simulated flow and successive cross-sections should not overlap. The procedure is initiated based on a first estimation of the possible extent of the flooded area (provided as input as well as the position of the river bed, see Figure 1.a), which is used to define the initial width of each section. The distances between profiles are then defined as a proportion of each cross-section width (proportion defined as input parameter). After each run, it is checked if the computed water level does not exceed the altitude of the borders of the

10 cross-section. If it is the case, the cross-section is enlarged in a proportion also defined as input parameter. Distances between profiles are adapted in consequence. Note that the final set of cross-sectional profiles and their location vary between the runs and depend in particular on the considered discharge value.

To ensure an automatic computation, important simplifications are introduced in the structure of the hydraulic model: cross-section shapes are estimated based on a simple extraction from the available DTM, without additional information on

15 topography or bathymetry; specific sections such as weirs or bridges are not represented; a unique roughness coefficient is used for all stream reaches (n=0.05 hereafter); no distinction is made between river bed and floodplain. Of course all these assumptions, even if necessary for sake of simplicity, may have an impact on the accuracy of the results. This point will be evaluated and discussed in the next sections.

An automatic check is performed after each hydraulic computation to eliminate the main errors in the shapes of cross-sections,

20 mainly associated with the limits of DTM information used as input: bridges still appearing in the DTM, remaining noise due to dense vegetation. This verification is based on the comparison between the wetted areas of the successive cross-sections: automatic removal of cross-sections appearing as inconsistent with the immediate upstream cross-section (ratio between successive wetted areas exceeding 3), before running again the hydraulic model.

One crucial aspect for the computation is the delimitation of the active river bed in presence of depressions in the floodplain

25 (perched rivers). In this case, the The choice of the input information (default extent of flooded areas and parameter values) highly influences the result and the computation time. For instance, a too wide initial flooded area or a too fast increase of cross-sections widths may lead to incorporate depressions of the flood plain (perched river bed) that are not connected to the river bed and hence not active for the considered discharge (see f Figures 1.b and 1.c). This may lead to both, overestimate the local extent of the flooded area and to decrease the simulated water level, with an impact on the upstream cross-sections due

30 to backwater effects. On the other hand, a too narrow initial flooded area and/or too slow increase of the widths of the profiles highly increases the computation time. To cope with these difficulties, the method offers the opportunity to modify manually any profile after a first iterative run. computations are first conducted for the smallest discharge (2-year flood), using a narrow initial extent of flooded area as input of the Cartino method. The width of the cross-sections are then progressively increased to detect as accurately as possible the limits of the river bed. If necessary, the remaining flooded areas disconnected from the

river bed are finally removed from the final result (Figure 1.d). The computed flooded area is then used as initial cross-section extent for the the next computation (next larger discharge value, see section 2.2), and so on.

2.2 ~~Computation of~~ Definition of the impact model based on a catalogue of flood extent maps

The hydraulic computations are conducted for each river reach of the considered stream network, and for a range of discharge

5 values corresponding to return periods of 2, 5, 10, 20, 30, 50, 100, ~~200~~300, 500, and 1000 years. The ~~downstream limit condition for each reach is the water level computed for the downstream river reach for the discharge of the same return period. The discharge~~ discharge quantiles are estimated based on the French SHYREG flood frequency database (Aubert et al., 2014). Nevertheless, the accuracy of this information on flow frequency is not crucial for the implementation of the impact model: it just enables to derive flood maps for defined discharges values of relatively homogeneous magnitude for all the considered

10 river reaches.

~~An automatic check is performed after each hydraulic computation to eliminate the main errors in the shapes of cross-sections, mainly associated with the limits of DTM information used as input: bridges still appearing in the DTM, remaining noise due to dense vegetation. This verification is based on the comparison between the wetted areas of the successive cross-sections: automatic removal of cross-sections appearing as inconsistent with the immediate upstream cross-section (ratio between~~

15 ~~successive wetted areas exceeding 3), before running again the hydraulic model.~~

~~One crucial aspect for the computation is the delimitation of the active river bed in cases of perched rivers. The computations are conducted step by step to limit the risk of including too rapidly flood plain depressions in the cross sections. For this purpose, the computations are first conducted for the smallest discharge (2-year flood), using a narrow initial extent of flooded area as input of the Cartino method. The width of the cross-sections are then progressively increased to detect as accurately as possible~~

20 ~~the limits of the river bed. The computed flooded area is then used as initial cross-section extent for the next computation (next larger discharge value), and so on.~~

All the computations are made in steady-state regime to simplify the procedure and facilitate its fast application at a large scale. The underlying assumption is that the extent of flooded areas is mainly influenced by the peak discharges, rather than the flow volumes. This assumption is consistent with the application domain of the method (flash-floods occurring in small

25 upstream watersheds). The discharge is assumed to be homogeneous on each river reach (no lateral flow introduced), the length of the considered river reaches being limited (2 km in average, see section 3). The roughness coefficient is fixed to n=0.05 according to the conclusions of Lumbroso and Gaume (2012) about the relevant range of roughness values in the case of flash floods. The downstream limit condition for each reach is the water level computed for the downstream river reach for the discharge of the same return period. For the last downstream river reach, the boundary condition corresponds to the normal

30 depth for a uniform flow regime. Finally~~In addition~~, a post-treatment procedure is applied to ensure a better overall consistency of the catalogue of flood extent maps~~. Computed flooded areas disconnected from the river bed are systematically removed form the final result (see figure 1d). And computed flood extent maps are~~: each map is corrected to systematically include the flood extents ~~maps~~ computed for the lower discharge values.

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Based on this catalogue, an impact model is derived for each river reach. The hillslope limits of the rainfall-runoff model are used to delineate the river reaches and the corresponding flooded areas (Figure 2.a). The assets present in the 10 estimated flooded areas are counted. The number of buildings may be used as an indicator of human asset exposure. More precisely, the number of private houses with a single and geo-referenced insurance policy in the available insurance database has been

5   considered herein to enable comparisons with the reported number of insurance claims (section 3.6). The values computed for the 10 flood extent maps for each river reach are then linearly interpolated to build a continuous relation between discharge and number of flooded houses, i.e. number of impacted insurance policies (Figure 2.b).

2.3   Main limits of the impact model obtained

Despite all aforementioned precautions, some sources of errors affecting the quality of results remain. These errors are mainly

10   related to the simplification of the procedure necessary for a fast and automatic implementation of hydraulic computations over a large river network. These errors are mainly due to:

   - errors in the retrieval of the shapes of the river cross-sections due to the automatic extraction and to the limits of topographic information used (DTM),

   - absence of representation of friction losses due to bridges and other hydraulic singularities,

15   - choice of a fixed Manning roughness coefficient, equal to 0.05,

   - steady-state regime computations,

   - remaining difficulties to determine the active river cross-section in cases of perched river bed despite the previously described precautions.

For these reasons, the information obtained should not be considered as a highly accurate estimation of flooded areas , but

20   as an estimation giving an and related impacts. It should nevertheless give an order of magnitude of the level of flooding and enabling some comparisons enable some comparisons of impacts at a regional scale.

2.4   From flood extent maps to impact assessment

Based on the catalogue of flood extent maps, an impact model is derived for each river reach. The hillslope limits of the rainfall-runoff model are used to delineate the river reaches and the corresponding flooded areas (figure 2.a). The assets present

25   in the 10 estimated flooded areas are counted. The number of buildings may be used as an indicator of human asset exposure. More precisely, the number of private houses with a single and geo-referenced insurance policy in the available insurance database has been considered herein to enable comparisons with the reported number of insurance claims (see section 3.6). The values computed for the 10 flood extent maps for each river reach are then linearly interpolated to build a continuous relation between discharge and number of flooded houses, i.e. number of impacted insurance policies (see figure 2.b).

2.5 The rainfall-runoff-impacts simulation chain

The impact model is finally incorporated in a full simulation chain combining radar-based quantitative precipitation estimates as input ((QPEs, see section 3) as input and a distributed rainfall-runoff model for the simulation of discharges over the stream networks. Quantitative precipitation forecasts or nowcasts may also be used as input of the chain to increase anticipation lead times. However, quantitative precipitation estimates QPEs have been considered herein to focus the analysis on the accuracy of the proposed rainfall-runoff-impacts simulation chain.

The CINECAR hydrological model (Gaume et al., 2004; Naulin et al., 2013; Versini et al., 2010b) was selected to build the simulation chain. CINECAR is a distributed rainfall-runoff model based on a representation of the catchment as a ramified series of stream reaches, to which both left and right-hand hillslopes are connected. The spatial resolution of the model (areas of hillslopes and associated length of river reaches) can easily be adapted and has been defined herein to match the resolution of the impact model. This means that the river reaches considered are identical in the rainfall-runoff model and in the impacts model: they correspond to the same stream network, defined here from an elementary catchment surface of 5 km^2.

CINECAR only simulates the rapid component of the runoff and is suited for modelling the rising limb and peak phases of significant flash-floods. For sake of simplicity, the hillslopes are represented by schematic rectangles of the same area as the actual hillslopes and the river reaches are assumed to have a rectangular cross-section. The width of the cross-section varies with return period of the discharge. The The Soil Conservation Service-Curve Number model (SCS-CN) is used to compute runoff rates and the corresponding effective rainfall at each computation time step (USDA, 1986). A temporal resolution of 15 min has been used here for the computations. The effective rainfall is then propagated onto both the hillslopes and the river network using either the kinematic wave model (Borah et al., 1980), or the Hayami solution for diffusive wave model (Moussa, 1996) to represent the flood wave attenuation in river reaches with slopes lower than 0.6%.

Since CINECAR was developed for the purpose of forecasting flood hydrographs in ungauged catchments, it includes a limited number of calibration parameters(Naulin et al., 2013): the width of river reaches. For sake of simplicity, the hillslopes are represented by schematic rectangles of the same area as the actual hillslopes, and the river reaches are assumed to have a rectangular cross-section. The width of the cross-section is the main parameter controlling the transfer function and is estimated based on the Strahler order of river reaches ; the and the discharge return period (Naulin et al., 2013). The Curve Number (CN) value is the second key parameter which controls the temporal evolution of runoff rates. The USDA method is used for the estimation of the CN (USDA, 1986), depending on the bedrock type, land useand antecedent rainfall, and 5-days antecedent rainfall for initialization. This model was applied in 2013 to the entire Cévennes Region (see section 3), and validated with respect to measured data (Naulin et al., 2013). It provided satisfactory results for large flood events, similar to the ones obtained with locally calibrated standard conceptual rainfall-runoff models, with an average Nash criterion computed for single flood events equal to 0.49.

The same model version has been used herein without any further adjustments for the Argens watershed (second case study), which characteristics are relatively similar to the watersheds of the Cévennes area. The performances of the model on this new application case study could be verified according to stream gauge and peak discharge data available for the June 2010 event.

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The discharge values computed with the CINECAR model are finally converted into estimated impacts according to the continuous discharge-impacts relations defined for each river reach (section 2.2 and Figure 2.b).

3   Presentation of the two case studies

3.1   The region of Alès in the Cévennes area, south eastern France, and the September 2002 flood

5 The region of Alès is located in the core of the Cévennes region, well known to be prone to frequent and intense flash floods (Gaume et al., 2009). Moreover, it has been identified during the implementation of the European Union (EU) flood directive as one of the areas the most exposed to flood risk in France (Areas with Potential Significant Flood Risk -APSFR- selected for the implementation of risk management plans). The region is presented in Figure 3, indicating the exact limits of the APSFR of Alès. Its vulnerability to floods is mainly related to the presence of the town of Alès, but also to other highly vulnerable

10 smaller towns such as Anduze (Figure 3).

This territory is part of three main watersheds: the Gardon d'Anduze, the Gardon d'Alès, and the Cèze rivers. These rivers have their upstream course in the Cévennes relief, and reach in their downstream part a plateau area with limited slopes. The APSFR of Alès is located in the transition zone between the mountainous and plateau areas. Therefore, this case study includes a large variety of river bed configurations including steep and narrow v-shaped valleys as

15 well as flat and wide floodplains. Some statistics about the river bed characteristics are provided in Table 1.

The region was hit on September 2002 by a catastrophic flash-flood event (Delrieu et al., 2005). A maximum rainfall accumulation of 680 mm in 24 hours was recorded in the town of Anduze, which is among the highest daily records in the region (estimated return period widely exceeding 100 years). The estimated peak discharges reached 900 [800-1000] $m^3.s^{-1}$ at Mialet and 3500 [3000-4000] $m^3.s^{-1}$ at Anduze on the

20 Gardon d'Anduze river, and 2500 [2100-2900] $m^3.s^{-1}$ at Alès on the Gardon d'Alès river. 23 casualties and 1.2 billion euros of damages were reported. This event induced a large number of insurance claims. It has therefore been selected herein for the evaluation of the impact simulation chain.

The area selected for the study corresponds to the exact limits of the APSFR of Alès (area of about 1000 km^2). It includes 400 km of river streams having at least a 5 km^2 upstream catchment area. The stream network has been divided

25 into 192 river reaches, among which only 70 reaches (132 km) are covered by the current operational flood forecasting service (forecasts published on the Vigicrues website: see the main river network on Figure 3.c).

3.2   The region of Draguignan in the Argens watershed, south eastern France, and the June 2010 flood

The Argens river watershed (2700 km^2) is located in the eastern part of the French Mediterranean region. It has been hit

30 by several severe flash floods in the recent years. This watershed was also selected as an APSFR for the implementation of the EU flood directive.

Among recent flash floods observed in this region, the June 2010 event is certainly the most catastrophic one. It particularly affected the region of Draguignan located in the eastern part of the Argens watershed (Figure 3), where the maximum rainfall accumulation exceeded locally 400 mm in 24 hours (estimated return period exceeding 100 years). The peak discharges were estimated to 440 [360-520] $m^3.s^{-1}$ at Trans-en Provence on the Nartuby river (tributary of the Argens river, see Figure 3), and

5 respectively 1000 [800-1200] $m^3.s^{-1}$ and 2500 [2200-2900] $m^3.s^{-1}$ on the Argens river at Les Arcs and Roquebrune-sur-Argens. 25 casualties and 1 billion euros of estimated damages were reported after this event as well as a large number of insurance claims.

~~The region of Draguignan is presented on figure 3.~~ As for the Alès case study, ~~it~~ the region of Draguignan presents a varied topography, and consequently a wide variety of river bed configurations, from narrow valleys in the upstream part of the studied

10 watersheds, to wide floodplains in their downstream part. The area includes 345 km of rivers with at least 5 ~~km^2~~ km^2 upstream catchment areas, which were divided into 173 river reaches. Only 42 of these river reaches are covered by the operational flood forecasting service ~~.~~ (Figure 3.d). This illustrates the possible added value of the proposed integrated flash flood impact simulation chain in France.

3.3 Available Digital Terrain Models

15 The implementation of the impacts models is based on commonly available high resolution DTMs in both case studies. Nevertheless, the characteristics of these DTMs significantly differ:

- a 20 m resolution DTM (interpolated at 5 m) produced in 2007 by the Conseil Général du Gard was available in the case of the Alès case study; its altimetric accuracy was estimated to less than 20 cm in non-vegetated areas, and less than 1 m in vegetated areas,

20 - a 5 m resolution DTM extracted from the ~~IGN~~ Institut Géographique National (IGN) RGE Alti database was available in the case of the Draguignan region; its ~~altmetric~~ altimetric precision ranges from 20 cm (main rivers covered with lidar data) to 70 cm (other areas covered with photogrammetry products for instance), and artificial structures such as bridges are removed in this DTM; this second product can be considered as standard DTM data that will be available over the whole French territory by the end of 2017.

25 It should finally be noted that if the terrain information used herein is now commonly available in France, its accuracy remains limited and may affect the quality of results: DTMs extracted from Lidar measurements are currently limited to the main rivers which are not the scope of this study, and would probably lead to results of better quality. The geographic coverage of Lidar data is however evolving very fast, and this data should become available also for small rivers in a near future.

3.4 Rainfall and discharge data

30 Both regions are equipped with relatively dense stream gauge and rain gauge networks, complemented with weather radars. In the case of the APSFR of Alès, the whole dataset was carefully checked in the framework of the Observatoire Hydro-Météorologique

Cévennes-Vivarais (OHM-CV~~research observatory (www. ohmcv.fr). ~~) research observatory. It can therefore be considered as exceeding conventional quality standards.

The locations of stream gauges are shown on ~~f~~ Figure 3. Given the limited possibilities to conduct direct flow measurements during intense flash floods, the rating curves are often extrapolated, with consequently a reduced accuracy of estimated discharges for high water levels and large floods.

Radar based QPEs are available for both case studies, at 1 km^2 spatial resolution and 5 min temporal resolution. They correspond to the operational Meteo France Panthere QPEs in the case of the Draguignan June 2010 event, and to a radar QPE reanalysis provided by the OHM-CV research observatory in the case of the September 2002 event in the region of Alès (Delrieu et al., 2009).

3.5 Reference flood maps from previous studies

Thanks to the recent application of the EU flood directive in both considered areas, a great effort was put on mapping flooded areas, leading to detailed inundation maps available for three reference events: the 30 year return period flood ("common" event), 300 year return period flood ("medium" event), and 1000 year return period flood ("large" event). These maps were generally obtained based on an 1-D hydraulic ~~modeling~~modelling, carefully implemented by experts in hydraulics. These maps were criticized and validated using all available information, including the observed extents of inundation during past floods such as the September 2002 and June 2010 floods. These maps were used as a reference here for the evaluation of the computed catalogues of flooded areas. Unfortunately these maps were produced on only part of the considered river networks. This limits the validation possibilities. In the case of the Alès case study for instance, the river network covered by reference maps represents 192 km (out of 400 km included in the case study) and includes 84 river reaches (out of 192).

3.6 Insurance claim database

During the last 15 years, an insurance claim database has been created and supplied by the Caisse Centrale de Réassurance (CCR) within the framework of its reinsurance contracts with its clients (Moncoulon et al., 2014). This database covers the whole French territory, and the quality of data is considered as acceptable for the period since 1997. It includes information on both nature and location of insurance policies and claims for all events classified as so-called "CATNAT" events. "CATNAT" are flood events with an estimated return period exceeding 10-years and consequently for which the natural disaster insurance compensation is activated, in accordance with the compensation scheme implemented since 1982 in France.

The CCR database is certainly the most comprehensive available database on flood field consequences existing in France. It has nevertheless some limits, and the content and accuracy of the insurance policy and claim data incorporated have evolved over the years. Consequently the data had to be carefully selected to enable an objective comparison with the ~~modeling~~ modelling results:

- With regard to the policies, the database nowadays includes more than 80% of the policies of the French insurance market, insurance against natural hazards being mandatory in France. A great effort has also been put on the accurate

geo-referencing of the policies in the recent years: approximatively 70% of the policies are geo-coded at the street number, about 15% geo-coded at the street center, and 14% geo-coded at the town centre. Only the policies accurately located (i.e. geo-referenced at the street number or center) could be considered here for incorporation in the impact model. Note that the address of the policy is generally the address of the owner of the asset. It does often, but not always, correspond to the address of the insured asset. Note also that in case of flats, several policies can be located at the same address, but are generally not all exposed to flooding. Therefore, only insurance policies and claims corresponding to private houses were considered here to ensure a more direct correspondence between houses, exposed policies and claims.

– As far as the claims are concerned, their collation in the database is less systematic: between 30 and 50 % of the total number of CATNAT insurance claims for the French market are documented in the database depending on the year. This depends on the comprehensiveness of the data provided by the insurance companies to the CCR. To base the comparison on faithful and robust data, the policies of the insurance companies documenting more than 80% of their claims in the CCR database were selected here for the validation of the forecasting chain. The claims with a null compensation amount were also removed, since there is no certainty in this case that a real damage occurred: at least, the amount of damage did not exceed the insurance excess in these cases.

Finally, only part of the database could be considered for the comparisons: geo-referenced policies, private houses, comprehensiveness of the information on claims provided by the insurance companies. A comparison with the IGN BD Topo database (buildings of < 7m height corresponding mostly to individual houses) shows that the number of selected policies represents about 20% of the total number of buildings in the considered floodplains (Table 2). The proportion is higher in the Draguignan 2010 case, sign of an improved quality of the CCR database since 2002. To enable a direct comparison of the forecasted impacts with the number of reported claims, the impacts model (Figure 2) was finally built based on the selected policies: the forecasted information corresponds in this case to a number of possibly impacted individual houses, for which almost comprehensive claim data is available. The details of the insurance data of individuals being confidential, the validation was based on claim data aggregated at the river reach scale. Moreover, to ensure a total confidentiality, the analyses and comparisons were only conducted on river reaches with at least 20 recorded policies in the database.

The analysis of the available claim data reveals some additional surprises. First, despite the comprehensiveness of the selected claim data, the ratio between reported claims and policies does rarely exceed 50% even in areas which are likely to have been flooded (Figure 4). Some houses with raised basements may be out of water even in the flooded areas, but not in such a high proportion. This ratio is also explained by the remaining proportion of claims not documented in the database (up to 20% according to the data selection), by the significant proportion of claims with a null compensation amount, and maybe also by some non-declaration of flood damages to the insurance companies. The large difference between the number of policies and the number of reported claims is a common feature for all floods in the CCR database (Moncoulon et al., 2014). In total, the combination of the limited proportion of selected insurance policies (policy/building ratio) and of the partial documentation of the claims and damages (claim/policy ratio) leads to a relatively low average ratio between the number of buildings and the

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number of reported claims in the floodplains: 6 to 9% (~~t~~ Table 2). This explains why, despite the richness of the CCR database, the evaluation of the proposed forecasting chain based on insurance claims, with the ambition to provide results at the stream reach level, had to be limited to extreme flood events with large numbers of reported claims.

The second major surprise is the significant proportion of reported claims located outside the estimated 1000-year flood envelop (over 10% for the two considered events, see ~~f~~ Figure ~~7~~4). This is also a general feature observed in the CCR database. Several explanations can be put forward to explain the presence of claims outside the identified flood areas: (i) damages may be induced by small watercourses not represented in the flood model, (ii) they may also be triggered by other local processes (runoff accumulation in low points, sewers saturation, cellar flooding due to groundwater raising, ...), and (iii) the address of the owners of the insurance policies may not correspond to the location of the affected assets. No information in the database enables a distinction between damages induced by direct stream flooding and other processes. The existence of a significant proportion of claims not directly related to river overflows represented by the model adds to the complexity of the validation exercise. For the purpose of this validation, and considering that the contours of the flooded area are only available for a limited number of the considered river reaches, every claim located in the maximum possible flood envelop (estimated 1000-year flood envelop) for each stream reach has been considered for the computation of the reference number of observed claims per reach. This could lead to overestimate the reference number of claims for reaches with actual limited flooding and will be discussed in the section presenting the results.

Despite all these constraints which limit the information content of the data, this CCR database is still a rich and unique source of information to measure the impacts of flash-floods in small rivers. It has been until now been used to assess economic losses at the event scale (Moncoulon et al., 2014). ~~It was worse testing~~ We tested herein if it could provide a number of private houses affected by the floods for each river reach, to be compared to the outputs of the proposed forecasting chain.

4 Results and discussion

As mentioned in the introduction, the results are presented hereafter in two steps:

- first, an evaluation of the accuracy of the catalogue of flooded areas is presented based on the Alès case study. Two different types of evaluations results are exposed: the water levels estimated at stream gauges are compared to existing stage-discharge relations (rating curves), and the estimated flooded areas are compared to reference areas computed for the purpose of the implementation of the EU flood directive.

- in a second step, the results of the whole rainfall-runoff-impacts simulation chain are presented for the both case studies, respectively for the ~~september~~ September 2002 and ~~june~~ June 2010 floods, and evaluated against real observed flooded areas and insurance claim data.

4.1 Comparison of water levels at stream gauges locations (Alès case study)

A first evaluation of the results of hydraulic computations is proposed here based on information available at stream gauges. These gauges indeed offer locally the opportunity to compare the rating curves based on expert know-how with the results of the 10 steady state hydraulic computations used for the implementation of the impacts model. Considering that the distance between cross-sections may reach up to 100 meters in the proposed method and that their locations is variable, additional cross-sections corresponding to the exact locations of the stream gauges were manually added for the hydraulic computations to enable comparisons.

The results are presented on f Figure 4 5 for three different stream gauges: Mialet, Banne, and Alès. This f Figure illustrates contrasted situations, which are detailed hereafter. It has first to be mentioned that only the Mialet and Alès stations are used for flood forecasting purposes: for these two stations, the rating curves have been extrapolated based on local hydraulic models. The Banne station is mainly used for low flows measurements and its rating curve was extrapolated based on an assumption on the hydraulic control of the gauging section: it is nevertheless an interesting case since the station is located on a small tributary.

The case of the Mialet station (f Figure 45.a) appears as an ideal situation, where the shape of the cross-section is well retrieved from the DTM and the computed water levels are very close to the existing rating curve. Note that the real measured discharge values are low for the three stream gauges. The comparisons are focussed on the extrapolation range of the rating curve: i.e. the automatically implemented hydraulic model is essentially compared with local expert know-how generally based on a detailed hydraulic computation. The very satisfactory result obtained in Mialet may be explained by the simple shape of the cross-section (deep and relatively narrow in this case), the limited presence of vegetation in the river bed that could affect local roughness, and the significant slope (i.e. limited risk of backwater influences). The selected roughness coefficient value of 0.05, an average value based on post-event studies (Lumbroso and Gaume, 2012), corresponds well to the locally adjusted one.

The comparison for the Banne station is less satisfactory (f Figure 45.b). The two cross-sections have similar shapes but do not seem to have the same reference altitude. A difference of about two meters exists for an unknown reason. This may nevertheless have little influence on the relative water levels and corresponding computed flooded areas. But, if the computed water levels are reduced by two meters, the computed discharges still appear much larger than the corresponding discharge estimates based on the local rating curve for the larger stage or discharge values. The slope of the local rating curve appears very low and does not even follow the evolutions of cross-sectional areas with the water stages. Such a rating curve shape could result form from a local backwater effect and could illustrate the limits of the hydraulic model used, that does not account for such phenomena. In this case, there is nevertheless no hydraulic singularity immediately downstream the gauge that could generate such an effect. The reference extrapolated rating curve is questionable.

The case of the Alès station illustrates other sources of difficulties (f Figure 45.c). Again in this case, the topography of the river bed appears well retrieved from the DTM even if a horizontal displacement is noticeable. But the shape of the computed stage-discharge relation, even if on average close to the rating curve of the station, appears chaotic and non monotonous. The

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stream gauge is located just upstream a large meandering where the valley is perched with a large flood plain on the right bank (~~f~~ Figure 4~~5~~.d). This flood plain is only inundated during extreme floods. Depending on the run (i.e. on the discharge value), it is included or not in the modelled cross-sections located just downstream the gauge and may generate an inundated area not connected to the river bed, finally eliminated in the post-treatment as described previously. But this artificial inclusion of the

5   flood plain in the cross-sections, for some intermediate discharge values, leads to under-estimate the computed water level at the gauged cross-section due to the backwater propagation (see longitudinal profiles in ~~f~~ Figure 4~~5~~.d). Clearly, the proposed procedure could not eliminate all the problems encountered when modelling perched rivers with 1-D hydraulic models, despite the precautions taken. The use of a 2-D hydraulic models could help solving the problems encountered in the future but at the price of a large increase of computation times. A detailed analysis of the results obtained for the two case studies nevertheless

10   reveals that the number of remaining problematic river reaches is limited. Moreover, these problematic configurations mainly correspond to relatively large rivers (~~315km²~~ 315 km² of drainage area at the Alès station), which correspond to the limit of the target application domain of the proposed method.

   Similar results were obtained for the other available gauging stations. Overall, the results are extremely satisfactory, almost exceeding the initial expectancies. The cross-sectional shapes can be correctly retrieved from the existing DTM despite their

15   limits, at least sufficiently accurately for the reconstruction of local stage-discharge relations. It is important to note that the ~~summer flow of~~ low-flows water heights are limited in these Mediterranean rivers~~is reduced~~. This explains why bathymetric data is not ~~really needed~~crucial to obtain a relevant estimation of the cross sections shapes: aerial topographic surveys are often sufficient to get an accurate representation of the river beds in these regions. The selected average roughness coefficient value appears to be suited to the local expert know-how. In the future, checking stage-discharge relations at gauging station

20   could help to adjust the values of roughness coefficients in the proposed approach extrapolated to other areas. It is important nevertheless to keep in mind that hydraulic singularities such as bridges, that can not be characterized through the DTM, may locally largely influence the stage-discharge relation, even if this could not really be illustrated on the presented case study.

4.2   Comparison with reference flooded areas (Alès case study)

Reference flood maps have been produced for the purpose of the implementation of the EU flood directive for discharges values

25   corresponding to the 30-year and 300-years flood events for almost half of the considered stream reaches. The automatically computed maps could be compared to these reference maps for the same discharge values. For each river reach, the estimated surface (ES) and observed or reference surface (RS) are compared. The surface in common (S_c) as well the excess surface (S_e: computed but not observed) and default surface (S_d: observed but not computed) are evaluated (~~see~~ ~~f~~ Figure 5~~6~~.a). Note that $ES = S_c + S_e$ and $RS = S_c + S_d$. A synthetic incoherent surface ratio (ISR) is ~~computed~~ then computed. It represents the

30   extent of excess and default surfaces, expressed as a proportion of the reference surface (eq. 1):

$$ISR = \frac{S_e + S_d}{RS} \tag{1}$$

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The permanent river bed (represented on ~~f~~ Figure ~~5~~6.a) which is not affected by estimation uncertainties, is not considered in the computation of the surfaces ES and RS and hence in the computation of ISR.

Figure ~~5~~6.b presents the distributions of ISRs computed for the 84 river reaches for which reference inundation maps were available (71 reaches for the 30-year flood) for the Alès case study. The results appear overall satisfactory: the ~~IRS~~ ISR ratio rarely exceeds 30 %. This ratio includes both default and excess surfaces: the real difference between ES and RS is in fact more limited. This suggests that the errors in the estimation of impacts will also be more limited. The ~~IRS~~ ISR ratio is sensitive to small differences between computed and reference maps as illustrated by the examples shown in ~~f~~ Figure ~~6~~7 and low values are difficult to reach and suggest a quasi perfect agreement. Figure ~~5~~6.c also shows that the ISR values depend on the magnitude of the simulated floods. The results obtained for the 300-year flood appear much more accurate, with ISRs almost never exceeding 50 %. This can be explained by the fact that the floodplains are largely flooded in case of high return period discharges, with limited possibilities for large errors. The estimation of the flooded areas for the 30-year discharges appear less accurate, with a significant proportion of stream reaches with large relative errors: ISRs exceeding 100 % for almost 10 % of the reaches. These relative errors are nevertheless essentially related to observed flooded surfaces lower than 0.1 ~~km^2~~ km^2 (~~f~~ Figure ~~5~~6.c). This corresponds to the very beginning of the river overflow that is hardly captured accurately with a hydraulic model based on automatic extractions from a DTM, whose roughness parameters are averaged over large areas and with no description of local hydraulic singularities. But large relative errors on small flooded areas will have limited influence on the impact model. Overall, the simulated flooded areas correspond pretty well to the reference areas. These results confirm the validation results obtained on the rating curves: the proposed 1-D hydraulic model, based on automatic extractions from relatively accurate DTM and on a regionally averaged roughness coefficient, stands overall reasonably well comparison with local expert-based hydraulic models, at least in the test region. Some reasons can be put forward to explain this result: the limited need of bathymetric data in the Mediterranean context; the river slopes - typically 0.5% or more - limiting the distance over which backwater effects propagate and therefore the local influence of hydraulic singularities not taken into account in the model; the reduced sensitivity of water stages (h) to variations of discharges (Q) due to the usual shape of stage-discharge relations ($h \propto Q^{3/5}$); and finally, the reduced sensitivity of the flooded area to the water stages, except at the beginning of the river overflow, due to the cross-sectional shapes of the river beds, with generally narrow valleys and well delimited flat flood plains.

4.3 Accuracy of forecasted flood extents for the Alès 2002 and Draguignan 2010 floods

For both considered validation flood events, observed inundated areas were carefully mapped after the floods on part of the affected streams. These observed flood extent maps were compared for each river reach to the forecasted flood extents. More precisely, the incoherent surface ratios (ISR) described in the previous section were computed based on the map of the flood catalogue corresponding to a discharge value immediately lower or equal to the ~~forecasted~~ simulated peak discharge value. There is indeed not necessarily a map in the catalogue corresponding to the exact value of the ~~forecasted~~ simulated peak discharge. This choice should lead to a slight underestimation of the flooded areas if the hydrological and hydraulic models were perfect. This is illustrated in ~~f~~ Figure ~~6~~7 which shows for some river reaches the observed flood extent and both extents

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corresponding the discharge values immediately lower and higher to the forecasted peak discharge. This ~~f~~ Figure also shows to what range of differences the ISR values correspond.

The ISR ratios obtained for both events are summarized in ~~f~~ Figure ~~5~~6.d. Without surprise, the ISR values are significantly increased when actual flood events are considered, if compared to the initial evaluation of the catalogue of flooded areas presented in the previous section. When actual floods are simulated, additional sources of uncertainties affect the computed flooded areas. The simulated peak discharge on which the forecasted maps are based may differ significantly from the observed ones. Moreover, the observed flooded areas may be the result of local processes (dike breaches, blockages) particularly during extreme flood events. These processes are not represented in the hydraulic models - the proposed simplified regional model or the local models used to elaborate the reference flood maps. In fact, ~~f~~ Figure ~~6~~7 shows that the differences between observed and simulated flood extents are not only explained by uncertainties in the ~~forecasted~~ simulated peak discharge values which would result in systematic over or under-estimations of flood extents, but also by local processes imperfectly accounted for in the hydraulic models.

Finally, a large proportion of the relative ISR remain lower than 50%. Consequently, the computed flood extent maps may be sufficiently realistic to provide an approximation of the local field consequences of floods and of their spatial distribution. This is verified in the next section. It is noteworthy that the ISR are higher in the case of the Draguignan 2010 flood even if the models (rainfall-runoff and hydraulic models) have been extrapolated to this event and area without any further calibration. It could be explained by the higher accuracy of the DTM available in this area. In any case, it is a promising results that seems to reveal that uncertainties related to the extrapolation of the models may be of secondary importance if compared to the other sources of uncertainties of the proposed approach. General conclusions can nevertheless not be drawn from one single example.

4.4 Validation of forecasted impacts based on insurance claims

Even after a careful selection of the appropriate validation data, the observed claim/policy ratio is significantly lower than 1 (~~t~~ Table 2 and ~~f~~ Figure ~~7~~4), and varies between river reaches. As exposed in section 3.6, this is explained by claims with no compensation and/or non-declared claims, buildings with raised basements, inaccurate location of insured buildings, and also the imperfect filling of the claim database. Clearly, the number of reported claims per river reach has a random component due both to the claim triggering processes and to the limits of the claim database. To account for randomness in the validation process, the number of reported claims can for instance be considered as the result of a random binomial process $B(n,p)$, n being the number of policies in the considered flooded area and p the probability that a corresponding claim with non-null compensation is observed. If p is considered to be the same for all reaches and equal to the average claim/policy ratio for the selected sample of insurance policies, a confidence interval (90% binomial confidence interval herein) can be estimated for the number of claims corresponding to every computed number of impacted policies (policies located in the estimated flooded area). Ideally, the average claim/policy ratio should be estimated inside the actually observed flooded area. However, this information is clearly not available everywhere on the considered stream networks. By default, the claim/policy ratios have been computed here within the 1000-year flood extent (Table 2).The result is presented on ~~f~~ Figure 8 for the two case studies.

This ~~f~~ Figure shows a relatively good agreement between the forecasted number of impacted policies and the number of reported claims per river reach. The observed spread of the results nevertheless exceeds the width of the 90% intervals, especially in the Draguignan 2010 case study: more than 10% of the dots lie outside the confidence limits with predominantly underestimations by the model. This indicates that some other sources of errors affect the relation between forecasted and

5 observed number of claims. First, the reported claim versus policy ratio is significantly affected by water depth and flood duration, two variables that have not been considered herein. Second, the claim/policy ratio and the reference number of claims ~~has~~ have been computed based on the maximum possible estimated flood envelop (1000-year flood envelop)~~to account for possible errors in the computed flooded areas. Since a significant proportion of claims are not related to the streams represented in the model (see section 3.6), this choice may~~, i.e. without using the observed flooded area (not available for a large part of

10 the stream network), or the computed flooded area (which has to be evaluated and should therefore not be used in the validation process). This may lead to slightly underestimate the claim/policy ratio since some not flooded areas are incorporated in the estimation. This choice may also lead to overestimate the reference claim number for stream reaches where limited overflow occurs, especially in densely urbanized areas (typically points A and B on ~~f~~ Figure 8.b), since a significant proportion of claims are not related to the streams represented in the model (section 3.6). The number of reported claims in the computed

15 flooded areas has also been estimated and the difference with the reference number of claims is indicated by the dotted lines on ~~f~~ Figure 8. This difference is modest in the Alès 2002 case, where the floods have been extreme over the entire considered area. The correction is much more significant in the Draguignan case, especially for almost all the points located over the 95% confidence limit (~~f~~ Figure 8.b). Several of these reaches, particularly points A and B, are located in the upper South-Eastern part of the studied area, which has not been affected by the most intense rainfalls. The observed flood extents were only partially

20 mapped in this area after the 2010 flood, but the mapped extent indicate moderate overflow in this sector and are in good agreement with the ~~modeled~~ modelled flooded areas. The high number of claims located outside areas flooded by the ~~modeled~~ modelled streams and the impossibility to separate these claims, as well as the absence of ~~reference~~ observed flood extent maps for stream affected by moderate floods clearly limits the use of the insurance claim database for the validation of flood impact models.

25 Finally, ~~f~~ Figure 9 compares the spatial distributions of the simulated peak discharges, of the maximum forecasted impacts (i.e. number of flooded private houses with geo-referenced policy) and of the number of associated claims according to the CCR database. It should be noted that information on claims is provided only for river reaches with at least 20 policies recorded in the database. This explains why no values have been provided for several stream reaches, essentially non-urbanized reaches with limited exposed assets. This ~~f~~ Figure illustrates the large differences in the outputs of the hydrological rainfall-runoff

30 model (~~f~~ Figures 9~~a and~~.a and 9.b), and of the integrated rainfall-runoff-impacts modelling chain (~~f~~ Figures 9~~b and c~~.c and 9.d) which provides a much contrasted analysis. It also shows a good overall consistency between the forecasted impacts (~~f~~ Figures 9~~b and c~~.c and 9.d) and observed claims (~~f~~ Figures 9~~e and~~.e and 9.f) for the location of the main hotspots. Apart from some exceptions, the ranking and magnitudes of the field impacts appears to be well captured by the proposed forecasting chain. That is mainly the information needed by rescue services to adapt and dispatch their rescue means during flood event

35 management. Such information could also help targeting more effectively alert messages.

5 Conclusions

Flood event managers need to assess, in real-time, the severity of possible field consequences associated to hydro-meteorological forecasts, to be able to take appropriate decisions. Automatic assessment methods are necessary in case of fast-evolving events such as flash-floods, when little time is available for information processing and analysis. Moreover, the direct estimation

5   of field consequences opens the possibility to test the performances of forecasting chains in ungauged areas, where various observations related to damages may be available.

This paper has tested the potential of simple approaches for the estimation of the magnitudes of possible field consequences within flash-flood forecasting chains. The proposed methods have been selected to be implemented with limited calibration effort, over extended areas and at detailed spatial scales. A particular attention has been paid to the performance evaluation of

10   the proposed chain. An original and particularly rich and comprehensive insurance claim data base has therefore been used. It is to our knowledge the first time an insurance claim data base is used for such a purpose.

The proposed approaches certainly deserve further validation, but the results presented herein on two case studies appear extremely satisfactory and promising. The flood mapping based on 1D steady-state hydraulic modelling, automatically implemented over a large river network with an average roughness value, stands the comparison, for most of the considered

15   river reaches, with local expert-based hydraulic simulations: stage-discharge relations at gauging stations and flood maps computed for the implementation of the European flood directive. The whole hydrological and hydraulic simulation chain provides maximum flooded areas that also appear generally close to the flood extents mapped after the two test events when such maps where available. The typical configuration of the streams affected by flash floods can be put forward to explain such satisfactory results: (i) narrow valleys and well-delimited ~~flood plains~~floodplains, (ii) limited need for bathymetric data for

20   Mediterranean streams, (iii) steep stream slopes implying limited spatial influence of hydraulic singularities (bridges) and their induced backwater effects, (iv) huge discharge contrasts between moderate, large and extreme floods that are well captured by rainfall-runoff models despite the inevitable ~~modeling~~ modelling uncertainties. The slightly better results obtained in the Draguignan case suggest that some improvements could still be achieved with more accurate topographic data, especially Lidar data enabling a better retrieval of the cross-sectional shape of the main stream bed. The influence of the DTM accuracy on the

25   results of the proposed approach will have to be tested. Some other difficulties nevertheless remain. The proposed ~~modeling~~ modelling approach has to be further improved to properly handle complex hydraulic configurations such as perched river beds (~~f~~ Figure 4~~5~~). And the observed flood extents may also locally differ from the estimated flooded area even if the discharge value has been well forecasted due to local effects difficult to anticipate such as blockages and breaches. A perfect fit is out of reach. This suggests that we should not put too much confidence in theoretical flood maps computed either a priori or in real-time.

30   Such maps, if provided to the flood event managers, should be presented as indications of possible flood scenarios close but not identical to the actual flood.

The validation of the estimated damages based on insurance claims faced some difficulties related to the specificity of insurance data. The CCR data base used is probably the most comprehensive source of information about flood insurance losses in France. However, the validation process requires both an accurate geocoding of insurance policies and a comprehensive

information on claims, which limits the amount of available information. A high proportion of claims is also not related to the streams included in the model, limiting the possibility to use this data as a reference for moderate floods if the actual flood extent is unknown (f Figure 8). The validation exercise could nevertheless be successfully achieved for the two extreme floods studied herein, providing an interesting additional information on the accuracy of the whole simulation chain. It should also be

5   considered that the quality of insurance data is continuously increasing and that some of the limits identified here (geocoding, comprehensiveness of claim information) should be significantly reduced in the future. Moreover, a better representation of the claims triggering processes should be possible based on the inundation water depths obtained from the hydraulic computations: direct relations between the claim ratios and water depths are indeed commonly used by insurance companies. Therefore, insurance claim data should be considered as a relevant option for the validation of flood forecasting results, particularly in

10 the case of flash floods affecting ungauged rivers. Despite this data is generally confidential, is may be accessible through partnerships with insurance companies. Other source of information on flash flood impacts could also be used such has the logs of emergency services, emergency calls, information shared on social networks (USDHS, 2012; Jongman et al., 2015; Tkachenko et al., 2017) or information gathered on the field after or during the event (Ortega et al., 2009; Ruin et al., 2014). This information is also affected by uncertainties and severe biases, especially in flash flood situations: absence of information

15 due to local breakdowns of communication networks, reduction of social network activity and partial filling of emergency logs in strongly affected areas during the paroxysm of the event... Some of this information has nevertheless the advantage to be available in real time (digitized logs, emergency calls, social networks) and could help validating and improving forecasted impacts. Finally, the combined use of flood impact forecasting models and field data mining and processing methods is without doubts a promising avenue for the development of innovative flood forecasting and warning services.

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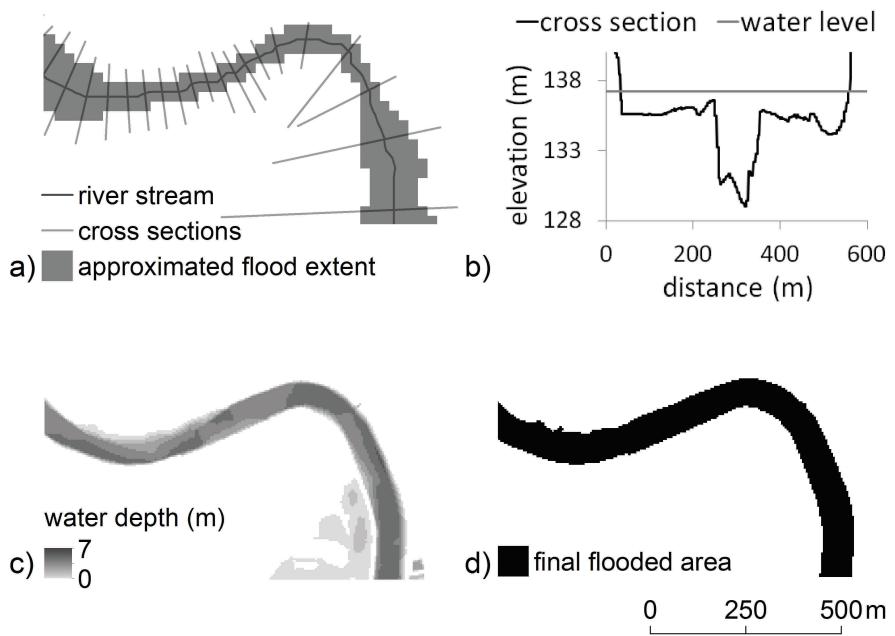
Figure 1. Overall principle of the computation of flood maps based on CartinoPC software: a) input information (position of river streams and approximated extent of flooded area) and position of cross-sections, b) example of one cross-section including the computed water level (1-D hydraulic model), c) map of flooded areas and water depths obtained after post-treatment, d) final map of flooded areas after removal of disconnected areas.
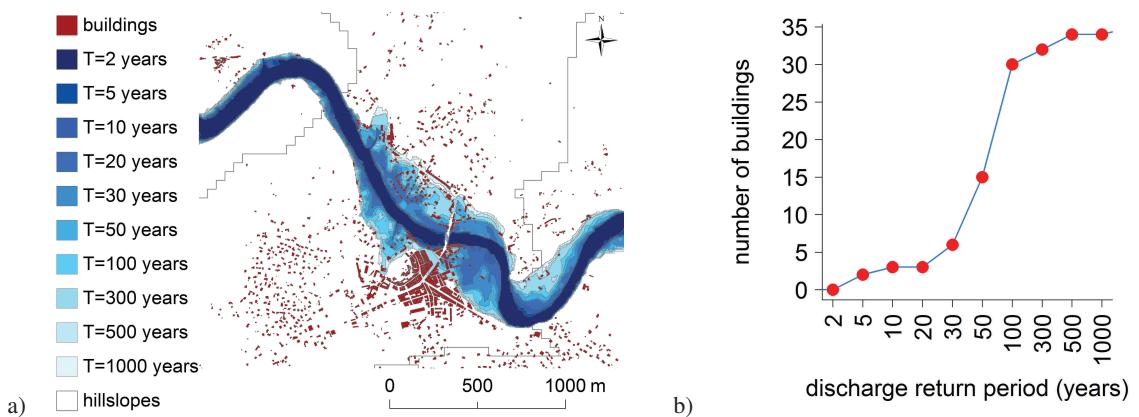

Figure 2. Illustration of the implementation of the impacts model on one river reach: a) ~~Catalog~~ catalogue of flooded areas, b) interpolated discharge-impacts relation.
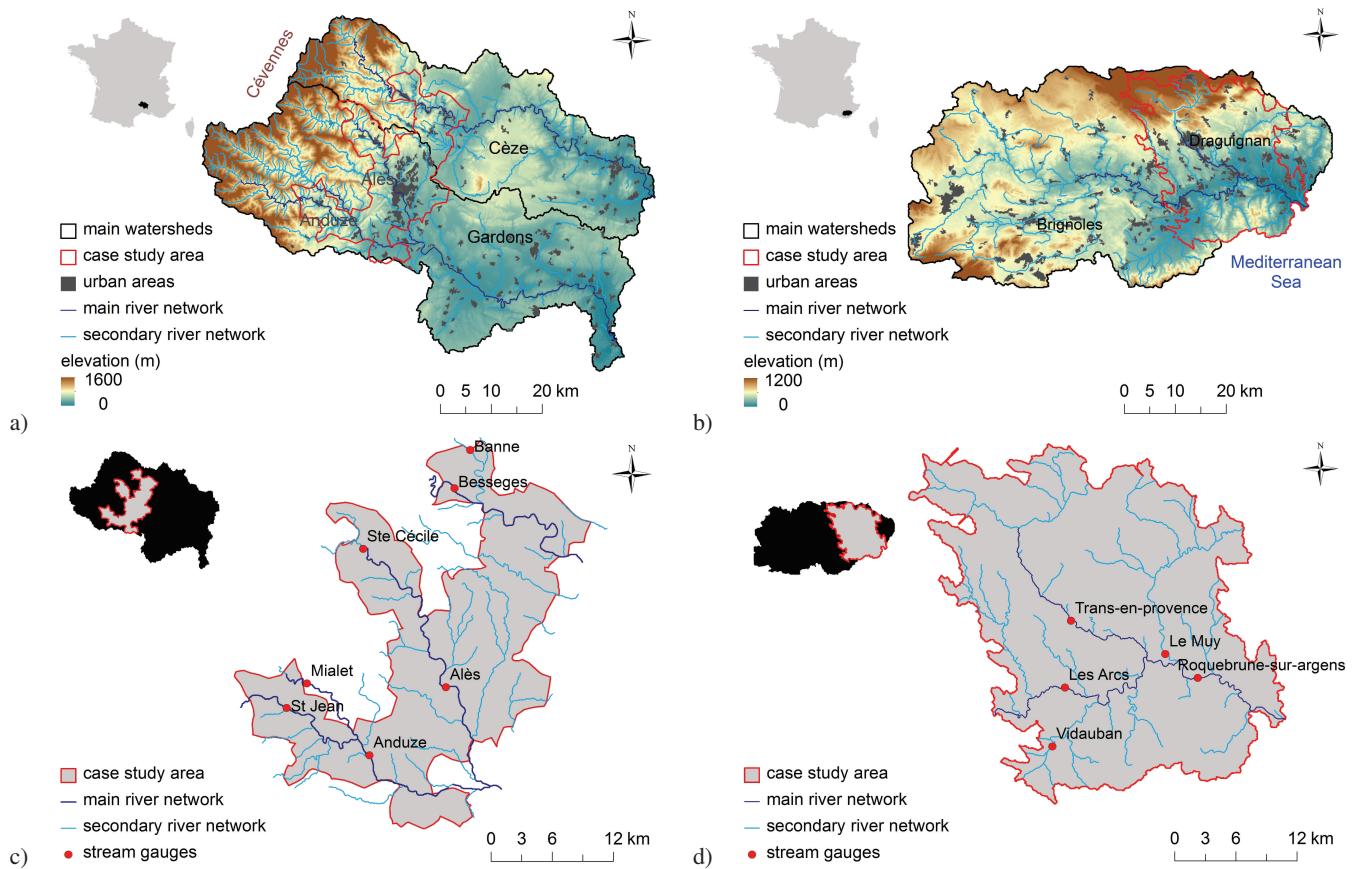
Figure 3. Location of the case studies: a) APSFR of Alès territory in the Gardon and Cèze watersheds, b) region of Draguignan in the Argens watershed, and river networks considered in the impacts models (5 ~~km^2~~ $\underline{km^2}$ upstream catchment surface): c) APSFR of Alès, d) region of Draguignan.

Table 1. Characteristics of the river networks considererered in the two case studies (extracted from SYRAH database)

Case study		bed slope (percent)	river bed width (m)	floodplain width (m)
		ave / min-max	ave / min-max	ave / min-max
Alès	main network	0.5 / 0.2 - 1	37 / 16 - 84	470 / 120 - 1670
	secondary network	3.4 / 0.2 - 20	7 / 2 - 34	430 / 60 - 3130
Draguignan	main network	0.6 / 0.1 - 1.2	25 / 5.5 - 41	730 / 130 - 3200
	secondary network	2.1 / 0.05 - 21	4 / 1 - 11	380 / 3 - 4800

Table 2. Mean claim/policies and policies/buildings ratios computed inside the ~~september~~ September 2002 and ~~june~~ June 2010 events. The claims and policies are those selected in the CCR database according to the rules described in section 3.6. The buildings considered are buildings of less than 7m height according to the IGN BD Topo database.

	Mean claims/policies ratio	Mean policies/buildings ratio	Global claim/buildings ratio
September 2002	0.37	0.17	0.06
June 2010	0.43	0.21	0.09

a) b)
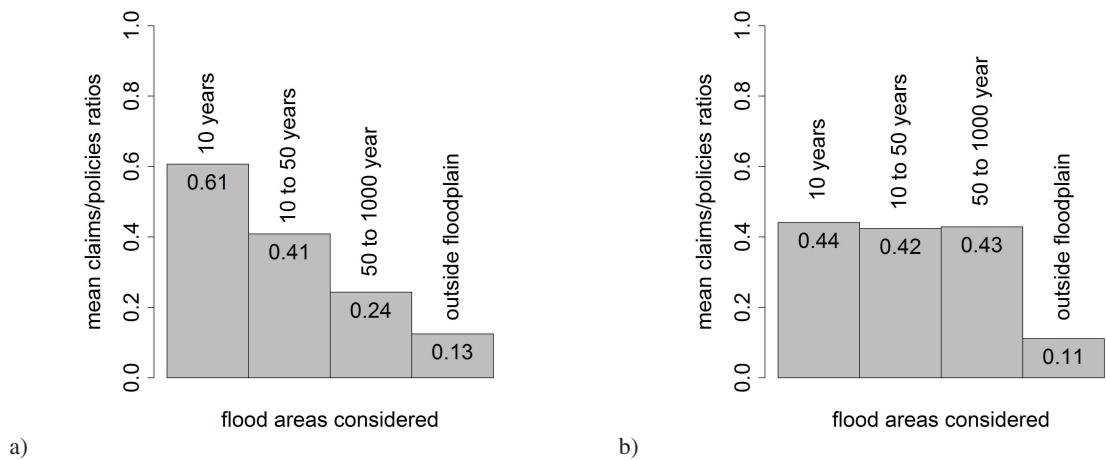
Figure 4. Spatial distribution of mean claim/policies ratios, inside and outside the floodplains: a) Alès 2002 event, b) Draguignan 2010 event.
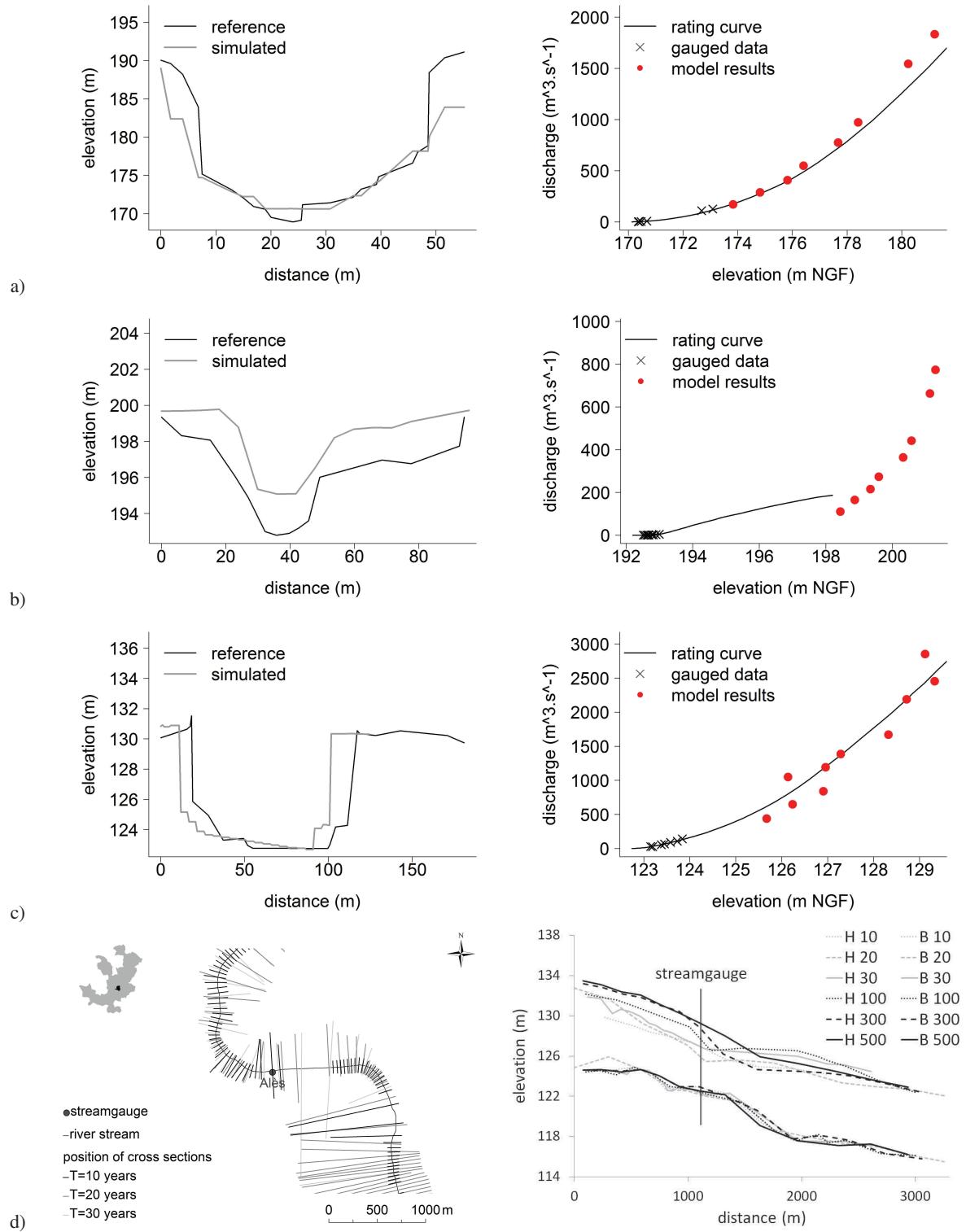
Figure 5. Examples of comparison of cross-sections and water levels at three stream gauges: a) Mialet station, b) Banne station, c) Alès station, d) Alès station: position of cross-sections and longitudinal profile of river bed (B) and water levels (H).
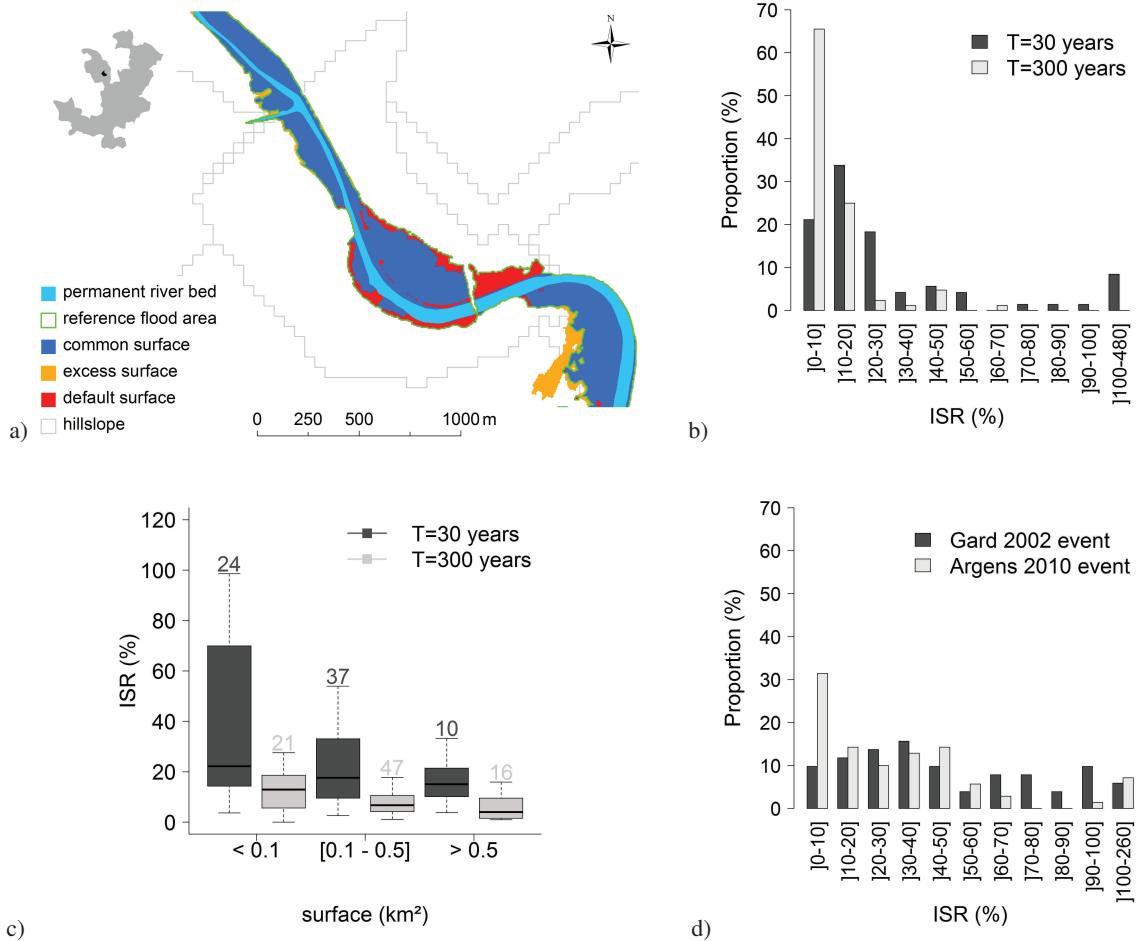
Figure 6. Comparison between estimated and reference flooded areas: a) definition of common surface (S_c), excess surface (S_e), and default surface (S_d) for the computation of ISR ratios, b) and c) distributions of ISR scores for the 30-year and 300-year discharge quantiles on the APSFR of Alès, and d) distributions of ISR scores for the full simulation chain for the Alès 2002 and Draguignan 2010 events.
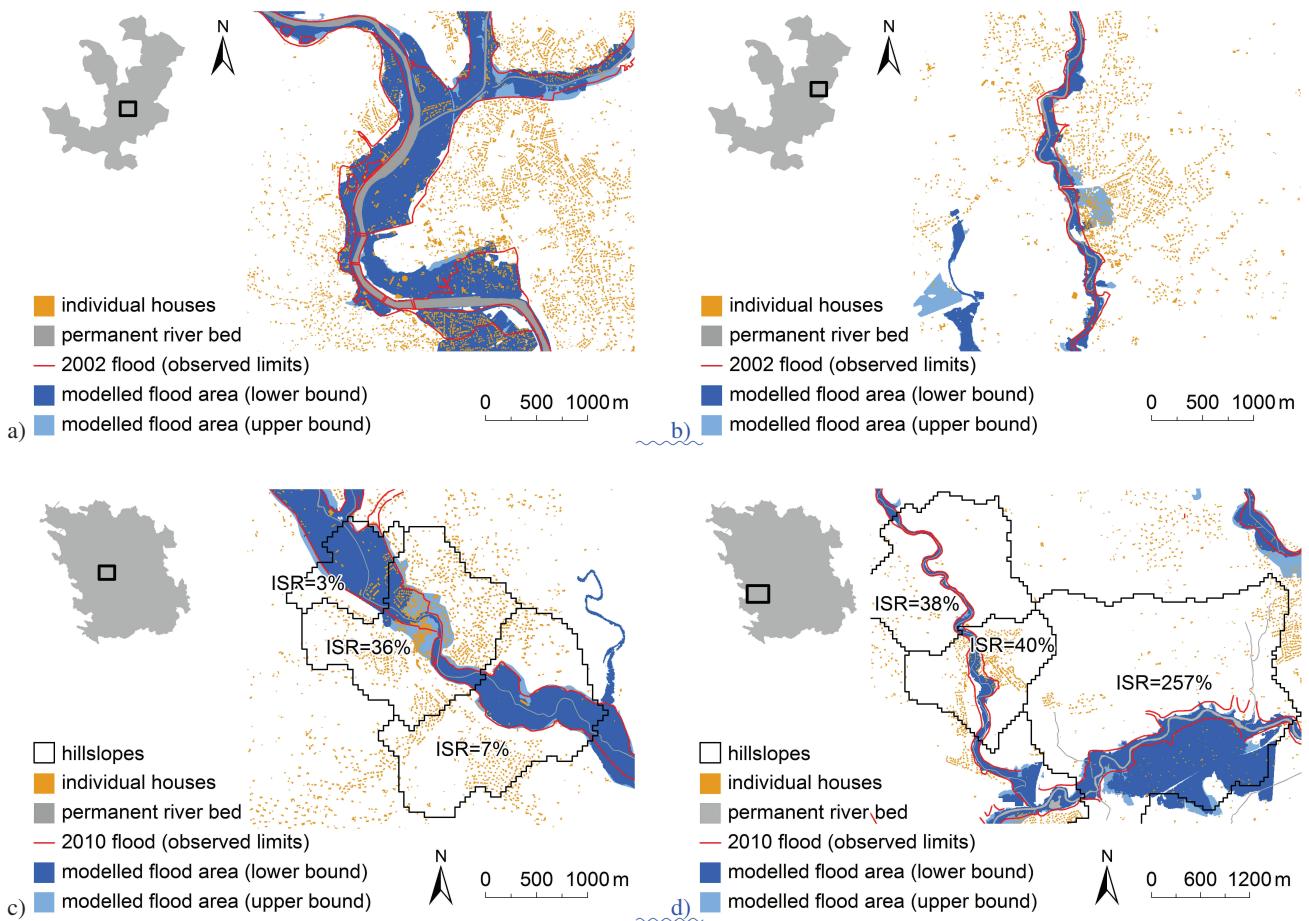
Figure 7. ~~Examples of comparison between observed and estimated flood extents, and related TSI values: a) Alès 2002 event for the Amous (left) and Avène (right) rivers, and b) Draguignan 2010 event for the Nartuby (left) and Florieye/Argens (right) rivers~~ Examples of comparison between observed and estimated flood extents, and related ISR values (computed for the lower bounds of estimated flood extents): a) Alès 2002 event for the Grabieux and Gardons rivers, b) Alès 2002 event for the Avène river, c) Draguignan 2010 event for the Nartuby river, and d) Draguignan 2010 event for the Florieye and Argens rivers.
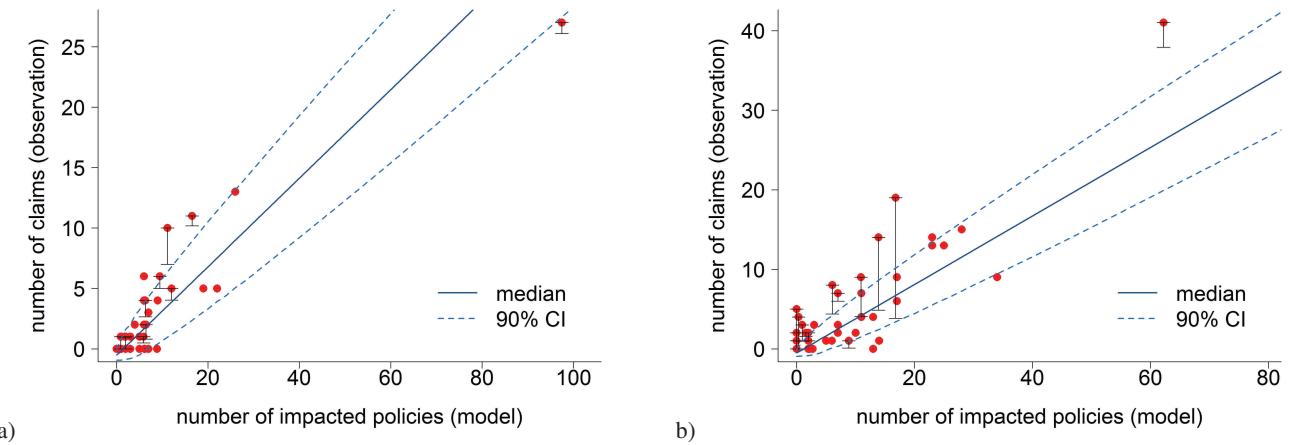
Figure 8. Comparison of estimated number policies affected by the flood (model), and associated number of claims for each river reach: a) Alès 2002 event, b) Draguignan 2010 event. Blue lines correspond to the mean claim/policies binomial relation and associated 90% confidence interval, vertical bars represent uncertainty on the number of claims related to river flooding.
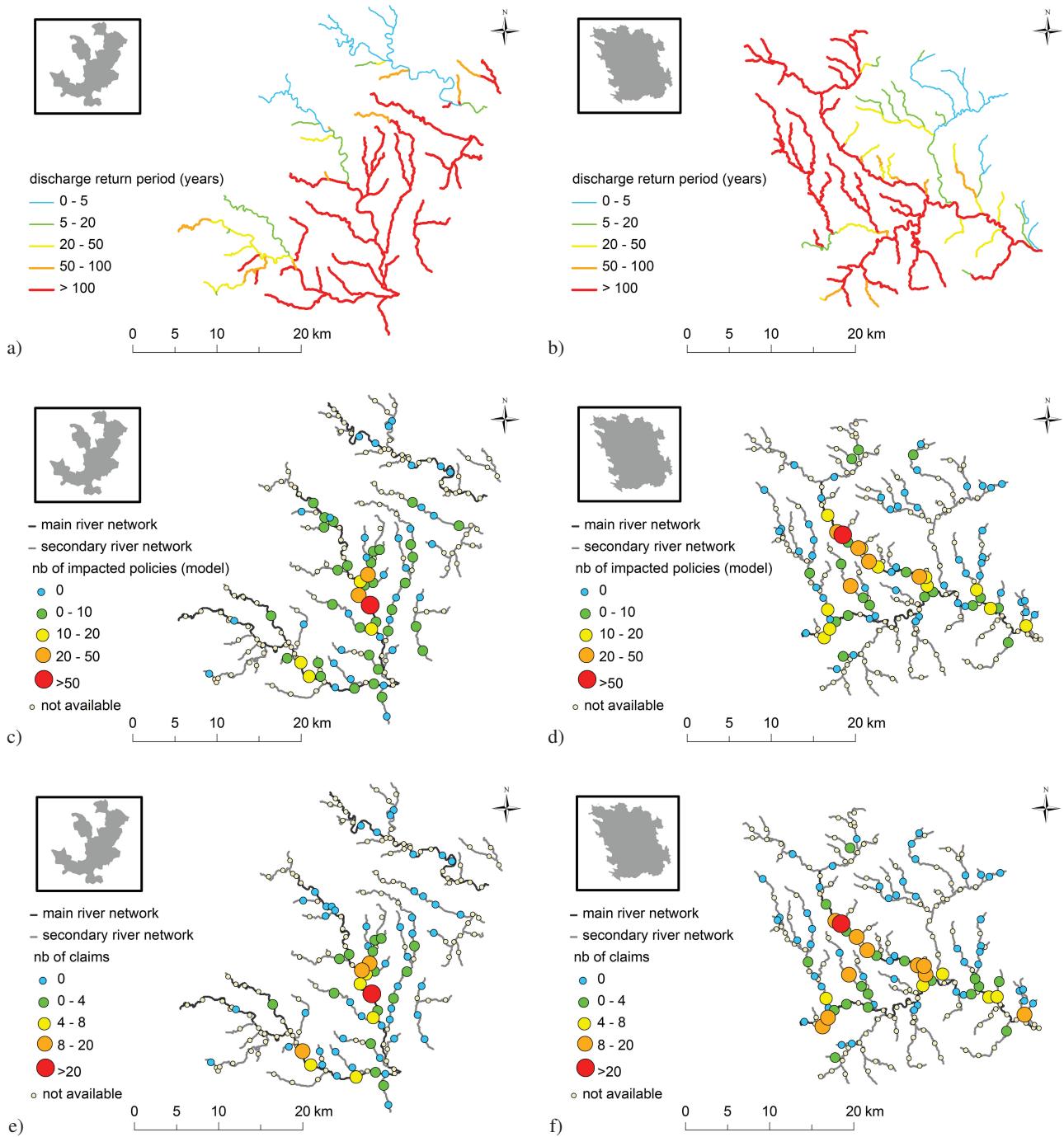
Figure 9. Maps of the peak discharges (return periods) and related impacts (number of flooded policies) simulated by the model, and of the number of claims extracted from the CCR database: a) peak discharges, Alès 2002, b) peak discharges, Draguignan 2010, c) estimated impacts, Alès 2002, d) estimated impacts, Draguignan 2010, e) claims, Alès 2002, f) claims, Draguignan 2010.