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Discussions

Analysis of the French insurance market exposure to floods: a stochastic model combining river overflow and surface runoff

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Abstract

The analysis of flood exposure at a national scale for the French insurance market must combine the generation of a probabilistic event set of all possible but not yet occurred flood situations with hazard and damage modeling. In this study, hazard and damage models are calibrated on a 1995–2012 historical event set, both for hazard results (river flow, flooded areas) and loss estimations. Thus, uncertainties in the deterministic estimation of a single event loss are known before simulating a probabilistic event set. To take into account at least 90 % of the insured flood losses, the probabilistic event set must combine the river overflow (small and large catchments) with the surface runoff due to heavy rainfall, on the slopes of the watershed. Indeed, internal studies of CCR claim database has shown that approximately 45 % of the insured flood losses are located inside the floodplains and 45 % outside. 10 % other percent are due to seasurge floods and groundwater rise. In this approach, two independent probabilistic methods are combined to create a single flood loss distribution: generation of fictive river flows based on the historical records of the river gauge network and generation of fictive rain fields on small catchments, calibrated on the 1958–2010 Météo-France rain database SAFRAN. All the events in the probabilistic event sets are simulated with the deterministic model. This hazard and damage distribution is used to simulate the flood losses at the national scale for an insurance company (MACIF) and to generate flood areas associated with hazard return periods. The flood maps concern river overflow and surface water runoff. Validation of these maps is conducted by comparison with the address located claim data on a small catchment (downstream Argens).

1 Introduction

Hydrological disasters occur when extreme events arising from a natural process cause severe damages to society. It is extremely difficult to predict both when and where hydrological disasters will occur and to estimate their potential impact. Although great progress has been made in short-term meteorological and hydrological forecasting, large uncertainties remain in respect of monthly or yearly predictions. Flood damages to society are multiple: human casualties, the decrease of economical productivity (and for exceptional events, productivity of a whole region), agricultural and residential damages. Impacts of major natural disasters have been classified in four types (Messner et al., 2007; Jongman et al., 2012): direct tangible (e.g. physical damage due to flood), indirect tangible (e.g. business interruptions), direct intangible (e.g. loss of lives) and indirect intangible (e.g. trauma). Property damage insurance losses can be classified as direct and indirect tangible losses.

Natural disasters in the world cause important economic losses, estimated in 2011 at USD 380 billion. Almost a third (USD 113 billion) was covered by insurance (Swiss Re, 2012). Global damages due to natural disasters have increased dramatically in recent years. This phenomenon can be explained by a continuous increase of the exposed values in the flood-prone areas (due to growth of population and wealth); an increase of vulnerability due to the growth of industrial dependency to networks (transport, electricity, telephone, etc.) and the cost of protection and a possible influence of global climate warming on extreme flood event frequency (Bates et al., 2008).

The financial losses covered by the insurance market, due to weather related catastrophes, are estimated in 2011 to USD 60 billion which represent 50 % of total insurance losses. The major historical flood events are estimated by (Swiss Re, 2012): US in 2012 (Sandy, 35 billion), Thailand in 2011 (12 billion), Germany/Czech republic in 2002 (2.9 billion), UK in 2007 (2.7 billion), Switzerland in 2005 (2.4 billion), Australia in 2011 (2.3 billion). In January 2013, flooding in Brazil, Turkey, South Africa, China, Indonesia and Australia has been estimated to several hundred million $ (Aon Benfield, 2013).

In France, according to law *82–600, 13, July, 1982*, a natural disaster (Nat Cat) is characterized by the abnormal intensity of a natural agent when the usual measures to be taken to prevent this damage were not able to prevent its occurrence or could not be taken. All compensations for natural disasters have to satisfy two conditions: a natural disaster must be recognized by an inter-ministerial decree and the property affected must be covered by a "property damage" insurance policy (legifrance.gouv.fr, 1982). Perils covered by the scheme are not explicitly named in the law, but the most recurrent are flood, ground movements (including subsidence since 1990), avalanches and, since 2000, cyclonic winds in the overseas departments and territories. Earthquakes are considered as a major exposure (in the south-east of France and in the Antilles) but no major event has occurred since 1982. The hazard threshold above which a natural disaster is recognized is not laid out in the official decrees. However concerning the hydrological flood disasters, legal precedents have converged to a 10 yr return period for river flow or a 10 yr return period for 1 h to 72 h rain.

In France, the insurance losses for the major flood events in the last twenty years estimated by CCR are: Rhône floods in December 2003 (950 M €), Xynthia storm surge in February 2010 (770 M €), Gard flash floods in September 2002 (680 M €), Argens flash flood in June 2010 (430 M €). The exposure to flood have several causes and 5 types of floods have been defined: slow river overflow on large watershed (e.g. downstream Seine river in 1910); groundwater floods (e.g. Somme River in 2001); flash floods (e.g. Argens overflow in June 2010); surface water runoff floods (e.g. Marseille floods in September 2000) and sea surge (e.g. Xynthia in 2010).

In 2010, the Nat Cat premium for the French insurance market represented 1351 M€ or 10 % of the global damage insurance premium. In the last 20 yr, floods and drought together represent 95 % of the total losses for natural disasters in France on the 1990–2010 period with 58 % (11.6 billion €) for flood and 37 % for drought. The average annual loss for flood is 509 million €in this period. The 3 most expensive year for flood damages are 2010 (1.4 billion €), 2003 (1.2 billion €), 2002 (1 billion €). Those losses are characterized by a large interannual variability.

CCR is a reinsurance company owned by the French state. Its first aim is to offer state-guaranteed coverage to insurance companies for extraordinary risks. Among these risks, natural disasters as defined in the Nat Cat scheme represent the major part of the reinsurance premium and losses.

Since 2003, CCR has developed an internal model for flood to estimate event losses, only a few days after a flood has occurred. This model constitutes the so-called "deterministic" approach. It is used for the publication of loss estimates for the major events for the insurance market, for the French government and for insurance companies (Moncoulon and Quantin, 2013). An historical event set has been built. It contains all the majors events (> 10 M€ insurance market loss) occurred on the 1995–2010 period on the French metropolitan territory. Each new flood event is added to the event set a few days after its occurrence, in order to estimate the losses to the insurance market. Two years after the event, CCR collects a sample of claims which is used for the calibration of the damage model.

In 2010, within the framework of the European Flood Directive, an objective assigned to CCR by the French Ministry of Finance is to estimate the exposure to floods for CCR, for the insurance market and for the French State. In the same context, flood hazard maps have been generated by the French Ministry of the Environment: the highest known floods (flood prone areas) and the modeled EPRI (for Evaluation Préliminaire du Risque Inondation – Preliminary evaluation of the flood risk) following the recommendations of the *handbook on good practices on flood mapping in Europe* (Excimap, 2007). In parallel, probabilistic flood models with damage estimation are developed by reinsurance brokers (Guy Carpenter) and modeling companies (Eqecat). The majority of these models only take into account river overflow with some of them taking partially into account non-riverine floods. In other European countries, flood hazard mapping methodologies have been developed in the recent, e.g. in the UK (Bradbrook et al., 2005), in Germany (Falter et al., 2012) or in the Czech Republic (Drab and Riha, 2009).

With an insurance loss exposure oriented goal, we have developed an original methodology based on the following hypotheses: (i) to estimate the flood exposure, heavy rainfall distributions must be combined with major river overflow – on the period 1990–2010, the flood losses for CCR are distributed as follows: 45 % for river overflow; 45 % for surface water runoff and 10 % for groundwater rise and seasurge (including Xynthia seasurge in february 2010) – (ii) the spatial distribution of rainfall on small catchments will have a significant impact on the spatial distribution of river flow (Poulard and Leblois, 2009) and thus on damages (iii) for major overflow events, the part of the losses due to heavy rainfall claims will be negligible.

For the first time in France, the authors have built a probabilistic flood map, homogeneous over the entire country (not including overseas territories), which combines river overflow and surface water runoff. For this purpose, a deterministic model, calibrated on the historical flood claims, is used to simulate the hazard and damages for each single event of a probabilistic event set. The event set originality is to combine a stochastic distribution of river discharges on large catchments with a stochastic distribution of spatialized rain fields on small catchments.

This paper is organized as follows: the first section describes the deterministic modeling methodology for hazard and damage simulations; the second section details the build of two probabilistic flood event sets (one based on stochastic river flow and one based on stochastic rainfall simulations) and their combination to generate a unique flood event set. In the third section the results are analyzed and discussed: the insurance loss estimations on a private insurance portfolio and the exceedance probability maps. Finally, the limits of this method are presented.

2 Deterministic model description

The components of the deterministic flood model are:

- The hydrological model (physical simulation of rainfall, surface water runoff and river overflow)
- The vulnerability and damage model (destruction rate and frequency curves)

2.1 Flood hazard model

The flood model is a rainfall-runoff model distributed on a 50 m grid, coupled with a river discharge model (Fig. 1). The input data for the flood model are described in Table 1. The digital elevation model (DEM) is used to define a regular grid of 50 m × 50 m over the entire French territory. The DEM is merged with a river database to create river segments.

A flood event for CCR is the occurrence of significant flood damages to the insurance market (exceeding an arbitrary threshold of 10 million €) due to heavy rainfall or river overflow. The flood event is defined by a geographical location corresponding to a rectangular area characterized by bottom left and upper right coordinates. The event duration is determined by two characteristic time limits: 24 h before the first significant rainfall recorded by Météo-France and 24 h after the last significant rain. Thus, each event has a minimum duration of 48 h. The average duration is 72 h.

2.1.1 Rainfall interpolation

For each cell of the grid, the efficient rain r is calculated as following:

$$r = p - \mathrm{etp} \quad (1)$$

where p is the hourly rainfall (mm) and etp is the daily potential evapotranspiration (mm). Both values are interpolated on the grid using a kriging method (Krige, 1951). The etp is considered as a constant value during the day and the daily value will be divided by 24 to estimate the hourly etp in order to be consistent with rainfall data. The choice of kriging method to compute the rain fields from the punctual measurements was motivated by (Arnaud and Lavabre, 2010). The exponential model of variogram is applied to estimate the variance.

$$\gamma(h) = 1 - e^{-h/l} \quad (2)$$

where h is the distance (m) between the stations and the kriging point $\gamma(h)$ is the variance at distance h. L is a calibrated parameter. Vegetation interception and depression storage during the rain event are neglected. The efficient rain (1 h timescale) is then provided on each cell of the grid. Rainfall interpolation is used for deterministic simulations based on Météo-France rain gauges. In the probabilistic approach, this section of the model is bypassed and spatialized rain fields are used as an input for the rainfall/runoff model.

2.1.2 Rainfall/runoff

The rainfall/runoff model is a water balance that estimates the water level noted h (m) and the soil water content θ (% of soil capacity) at each time step t for the entire flood event duration. In a simplified approach for large scale simulations, the surface water balance can be estimated for small time steps and small surface units as follows:

$$\frac{\delta h}{\delta t} = r - i + q_{\text{in}} - q_{\text{out}}(-\text{riv}) \qquad (3)$$

where h is the quantity of surface water (mm), t is the time, r is the efficient rain (mm h^{-1}), i is the infiltration flow (mm h^{-1}), q_{in} is the runoff flow of surface water from adjacent cells (mm h^{-1}) and q_{out} is the runoff flow of surface water to adjacent cells (mm h^{-1}). The water flow to the river network riv is only taken into account for identified river cells.

The soil wetness θ is estimated by Eq. (4):

$$\frac{\delta \theta}{\delta t} = i - l + u_{\text{in}} - u_{\text{out}} \qquad (4)$$

where θ (mm) is the soil wetness at time t, i is the infiltration flow (mm h^{-1}), l is the leaching flow from the soil reservoir to the underground water (mm h^{-1}), u_{in} is the groundwater drainage from adjacent cells (mm h^{-1}) and u_{out} is the groundwater drainage to adjacent cells (mm h^{-1}).

The elevation grid used for slope calculation is:

$$E = \mathrm{ALT} + h_t \quad (5)$$

where E is the elevation (m), ALT is the constant elevation given by the DEM (m). h_t is the level of surface water (m) on the grid at time t. For each time step, the slopes are calculated to take into account the changes in surface water level. Slopes are calculated in the 8 directions. Ag is the sum of the 8 slope gradients (G) on a cell. p is the square root of the sum of the square of the 8 slope gradients. As p is dependant on h_t, p_t is computed at each time step. To distribute the water in the 8 directions, the ratio R is estimated by:

$$R = \frac{G}{\mathrm{Ag}} \quad (6)$$

Only the positive differences are considered.

The water velocity is calculated on each cell using the Manning equation (Manning, 1891). Each square grid (50 m × 50 m grid size DEM) is considered with a constant and homogeneous slope, a constant and homogeneous water level and land cover.

$$v = K \cdot h_t^{2/3} \cdot \sqrt{p_t} \quad (7)$$

where K is the Manning rugosity coefficient ($\mathrm{m}^{1/3}\,\mathrm{s}^{-1}$), h_t is the quantity of surface water (m) at time t and p_t is the square root of the sum of the square of the 8 slope gradients ($\mathrm{m\,m}^{-1}$). The instantaneous water velocity v is expressed in $\mathrm{m\,s}^{-1}$. The potential volume leaving the cell during time step t is v_{pot} and is derived from water velocity v by:

$$v_{\mathrm{pot}} = v(h_t \mathrm{d}x) \quad (8)$$

With dx being the grid size (m). The potential runoff (q_{pot}) represents the amount of water that could leave the grid cell during one time step regarding the water velocity.

This amount of water is limited by the quantity of water present on the grid cell at time t. This amount of water is called the total volume v_{tot}. It is calculated at time t on the grid cells and depends on the surface water (m):

$$v_{\mathrm{tot}} = h_t \mathrm{d}x^2 \tag{9}$$

The model will calculate at each time step the amount of water that leaves a grid cell for the adjacent cells, depending on the slope in the 8 directions: for example for one direction (south), the estimated runoff flow q_{out} (mm) will be:

$$q_{\mathrm{out}_{\mathrm{south}}} = 10^3 \cdot \frac{\min(v_{\mathrm{pot}}, v_{\mathrm{tot}})}{\mathrm{d}x^2} \cdot R_{\mathrm{south}} \tag{10}$$

Two types of cells are defined on the DEM grid: non-river cells and river cells. A cell is identified as a river cell if a river segment crosses it. All water amounts entering a river cell by surface runoff production will be added to the river flow model as an input at the same time step t. This full amount of water will be lost for rainfall/runoff model and will leave the river cell definitively and join the routing model (see below).

The model is a single soil reservoir with a maximum volumetric water content of 20 %. This maximum soil wetness is constant for the entire grid. Infiltration flow from the soil surface to the soil reservoir is derived at each time step from the Green and Ampt equations (Green and Ampt, 1911):

$$i = \mathrm{Ic} + \frac{b}{\theta_t} \tag{11}$$

where i is the infiltration flow – the volume of water entering a unit soil surface per unit time (mm h^{-1}), Ic being the asymptotic steady infiltration flow reached when t become large (mm h^{-1}), b is the infiltration decrease (mm^2 h^{-1}) and θ_t is the soil wetness expressed in mm.

The infiltration flow is mainly dependent on the amount of water available on the soil surface and on the soil wetness. Infiltration decrease parameter (Id) has been modified on each grid cell using a coefficient K with value ranges from 0 to 1 depending on the Land Cover:

$$b = (1 - K) \cdot \mathrm{Id} \tag{12}$$

At each time step, the following equation is proposed to estimate the groundwater drainage:

$$u = \max\left(0.1\ ,\ 10 \cdot \sqrt{\theta_t}\right) \tag{13}$$

where u is the groundwater drainage ($u = 0.1\,\mathrm{mm\,h^{-1}}$) for unsaturated soils and $10\,\mathrm{mm\,h^{-1}}$ for saturated soils, θ_t is the soil wetness at time t (as a ratio of the maximum volumetric water content). The groundwater drainage is then distributed in 8 directions depending on the slope.

2.1.3 Hydrological river routing

A simple hydrological river routing method is used to determine river flow, water level and overflow areas in the floodplain (Fig. 1). The river is considered as a succession of river segments which are individually homogeneous in terms of section shape, width and slope. Time step of the routing model is shorter than rainfall/runoff model to take into account the higher velocity of water in the river bed. A 10 min time step has been chosen. At each time step, the volume of water in the river segment is computed with Eq. (14) and the following inputs and outputs:

Inputs:

- The river flow of the upstream section s0 (Q_{t-1}^{s0}) during time step $t-1$
- The river flow of the tributary sections sA (Q_{t-1}^{sA}) during time step $t-1$
- The outputs of rainfall/runoff model rr: surface water runoff to the river cells (Q_t^{rr}) during time step t

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Outputs:

- The river flow of the downstream section s2 (Q_t^{s2}) during time step t
- The flow of water leaving the minor riverbed in case of overflow (Q_t^{deb}) during time step t

$$Q_t^{s1} = v_{t-1} + \frac{\delta v^{s1}}{\delta t} = \left(Q_{t-1}^{s0} + Q_{t-1}^{sA} + Q_t^{rr}\right) - \left(Q_t^{s2} + Q_t^{deb}\right) \tag{14}$$

The river flow at time t is compared with a threshold defined for each section by the higher value between the 10 yr return period flow and the return period that characterizes the efficiency of the protections against flood for that section, if there are any. The flood protection database used for this study has been developed in CCR and is not exhaustive. The flood protection overflow is taken into account when the information exists but the breach risk is not modeled in details.

The river overflows if Q_t^{s1} exceeds the threshold. The depth in the riverbed is not taken into account when the river segment does not overflow. Indeed, with the 1 – m elevation precision of the DEM, the river bed shape does not appear in the grid. Thus, in case of overflow, all level of water above the river banks will appear on the DEM and will be propagated. The volume of water exceeding the threshold for a river segment is propagated on the DEM in 8 directions using the Manning equation – same as for rainfall/runoff model. The K-Manning values are estimated from land use (Corine Land Cover). The shape of the major riverbed is estimated from the DEM values. The lack of precision in the elevation grid will induce approximations in the expansion of the flood which will have higher impacts than the uncertainties in river flow estimations. This finding is consistent with that which can be found in (Bradbook et al., 2005). Slope is derived from the DEM: each river segment AB is considered to have a uniform slope measured by the gradient between point A and point B. The minor riverbed width estimation has been done using the river width classes described in BD Carthage. All rivers have been classified into 4 width classes:

[< 5 m ; 5–15 m ; 15–50 m ; > 50 m]

DEM grids which are concerned by a positive water level are included in the flood area polygons.

2.2 Vulnerability and damages modeling

The damage model is used to estimate the cost of flood events based on information on hazard and vulnerability. Hazard informations which indicate flood intensity areas are combined with vulnerability information which provides flood sensitivity information per insured risk. For more than 10 yr, CCR has collected insurance portfolio data in the context of trade relations with its clients. The risk and claim size, in 2013, represents 328 million risks and 1.8 million claims. The 1995–2010 period is the richest in terms of representativity of the risks and claims. Depending on the year, up to 70 % of risks and 50 % of claims for the French insurance market are gathered in the database. All risks and claims are then geolocalized with the following results: 52 % of the risks are located at the street number precision; 24 % at the street center precision; 23 % at the commune level and 1 % unlocated.

The hazard model output data used in the damage model are:

- Water depth for river overflow (m)
- Water discharge for surface runoff ($m^3 s^{-1}$)

These values are the output of the simplified hazard model. They do not represent measurable physical quantities, but the order of magnitude of input data used to calibrate the damage model and to map the exposure.

The vulnerability data used in the damage model are:

- Insured values

- Risk location
- Floor
- Building type
- Industrial activity

The damage functions are calibrated on a selection of historical events from the historical event set on the 1995–2010 period. These events are selected on the following characteristics:

- Market share of risks and claims in the CCR database for the year of occurrence
- Quality of hazard simulation
- Variety of flood types and geographical situation

The cost of flood is calculated for insurance market or for an insurance company by using the following process:

- Estimation of Nat Cat occurrence probability for each commune
- Estimation of Nat Cat recognition probability for each commune (i.e. the official decree)
- Estimation of the claim frequency and the damage ratio for each risk

The various estimates are the result of models calibrated on past events. The comparison between the historical losses and the simulated losses for a selection of flood events is shown in Table 6. This calibration step gives reasons to be confident in the simplified approach. The distribution of damages for a single event, based on the uncertainties in the simulation of the calibration event set, is shown in Table 7 for an historical event.

3 Generation of a probabilistic flood event set

To achieve our goal, which consists in estimating the exposure of the French insurance market to floods, we need to associate a return period to any amount of annual damages. A flood event is characterized by a single spatial and temporal intensity distribution. It is almost impossible to estimate the global return period of a single event and a same amount of annual damages can be caused by an infinite number of single events. To estimate the probability distribution of damages our idea is to use a Monte-Carlo approach by simulating a large number of single flood events with the deterministic model. Because our historical event set may not be representative enough, we have to build a fictive event set. Fictive events must be realistic and have to be consistent with historical events statistic behavior. In this study, exposure to floods is limited to river overflow and surface water runoff which represent 90 % of the flood damages in the last twenty years. First, fictive river flows are generated on a selection of flow stations for a river database (Quantin, 2011; Moncoulon and Quantin, 2013). This generator is calibrated on historical river discharge records in the Ministry of Environment database (banque Hydro, 2006). This approach is called the *F1* model. The second method uses the fictive rainfall generator SAMPO-TBM (Leblois and Creutin, 2013) calibrated on the Météo-France SAFRAN rainfall database (Durand et al., 1993) to create annual series of hourly rainfall and simulate the flood events associated. This approach is called the *F2* model. Then both event sets are combined to create a single library of flood events and create hazard maps and damage distribution.

3.1 *F1* model: the generation of fictive river flow

The general principle is to generate years of monthly fictive river flows, in order to detect river overflows for the constitution of a library of multiple single events.

Different types of river flow are available in the "Banque Hydro": average daily values or maximum values per month. The maximum values per month are chosen to avoid the underestimation of extreme values due to the average daily data. Statistical distributions are fitted separately for each gauge data. The minimum period of records necessary to be considered is set to 30 yr. A sample of 802 stations out of 2200 is selected.

The distribution of flow data for a single station is not homogeneous: e.g. river flows in January are strongly different from river flows in August. Furthermore, river flows for 2 successive months are not necessarily independent: a monthly maximum value can occur the last day of month 1 and the first day of month 2. To work on independent and homogeneous data, a set of 9624 variable are defined: 802 stations for 12 months. The dependence between the 9624 variables are represented by a Gaussian copula (Nelsen, 1999; Quantin, 2011). Sklar's theorem (Sklar, 1959) on Copulas allows us to model a multivariate distribution in two separated parts: the individual behavior of each marginal with empirical or fitted distributions and the dependence between marginal with a Copula. There are several common families of copulas such as Gaussian, Archimedean. A Gaussian copula has a single parameter: the correlation matrix of the variables.

Based on this method, 1000 yr of maximum monthly river flows are generated. For each year, 9624 values are generated: 12 maximum monthly river flows for each station. In our approach, the river flow generated for the different stations of a same river (or its tributaries) are considered independent. The river flow values generated on a gauge station will be propaged on the river segment until another value generated on another gauge is present (Fig. 6).

This library of stochastic river discharges is used to create fictive flood events: an overflow event is created when at least one value of flow for one station is above the 10 yr return period value. This 10 yr threshold has been chosen to be consistent with the Nat Cat recognition ratio applied in the Nat Cat scheme.

As described in the Banque Hydro, the French metropolitan territory is divided in 7 catchment areas: Artois-Picardie, Bretagne, Adour-Garonne, Loire, Rhin-Meuse, Rhône-Méditérranée-Corse and Seine-Normandie.

With this method 1000 yr of continuous fictive flows are generated. From this simulated flows, 18 057 events are created. Each event is simulated with the river routing model which will be forced by the simulated river discharges. The rainfall/runoff model is bypassed in this method. This simplified deterministic model is used to calculate the impacts of each event in terms of hazard and damages. For each event in the event set, the analysis of uncertainties in the damage distribution is calibrated on the simulation of the 1995–2010 historical event set. This probabilistic distribution is called *F1*.

3.2 F2 model: the generation of stochastic rain fields

3.2.1 Input data

We use an extract of the Météo-France database SAFRAN (reanalysis of atmospheric surface fields): a 8 km resolution over France for the period 1958–2010 for daily and hourly rainfall (Durand et al., 1993). This database was generated by the Météo-France SAFRAN-ISBA-MODCOU analysis system. These data are homogeneous over the period and over the entire territory. In 2011, 184 million data of daily rainfall and 4.416 billion data of hourly rainfall are recorder in the SAFRAN database and used for the calibration of the method.

A local rainfall climate is considered as a succession in time of several rainfall types including the dry weather type (i.e. no local rainfall). Homogeneous areas, a.k.a. small catchments, have been defined. At every point of a given small catchment, for a given time, only one rainfall type can occur.

Each rainfall type is considered as a random process defined by 3 parameters: the average (μ) and the standard deviation (σ) of non-null rainfall and the average spatial rate (τ) of non-null rainfall coverage (i.e. the number of non-null rainfall SAFRAN grid cells out of the total number of SAFRAN grid cells for the small catchment).

3.2.2 Spatialized rain generator

The non-zero precipitation field is derived from an unit Gaussian field. The indicator field (1 for rain and 0 for dry weather) is obtained by thresholding an independently simulated Gaussian field. The spatio-temporal Gaussian fields are generated by the turning band methods TBM This method generates non-conditionnal stochastic simulations in 3 dimensions (2 in space and 1 in time) from a large number of one-dimensional simulations called “band” (Matheron, 1973). The homogeneous spatiotemporal simulator is described with more details in (Leblois and Creutin, 2013). This simulator has been used to prove the importance of rainfall spatial distribution for the design and sizing of flood control structures (Poulard and Leblois, 2009).

3.2.3 Long-term rain sequences simulation

To build rainfall types we use a purpose oriented typing of observed rainfall data. The sequences of hourly precipitations are summed to 6 h cumulative values characterized by: the average and the standard deviation of non-null rainfall and the average spatial rate of non-null rainfall coverage (see above).

These descriptors are organized by a Kohonen self-organizing-map (Kohonen, 1995) to build several types and allocate individual time-steps to one of these types. For this study, 25 types of wet weather and 1 type of dry weather have been defined. One set of parameters is derived for each rainfall type. The qualitative sequence of rainfall types is described by sequencing algorithms. The sequence of rain types in time are analyzed and simulated by using the transition probability matrix from one type to the others.

3.2.4 Simulation process

In the first step, the SAFRAN rain fields are selected on the small catchment and analysed with the Kohonen self-organizing-map to create 25 types of wet weather and 1 type of dry weather. Then the transition probability matrix is applied to simulate long term rain sequences. These rain sequences are characterized, on the small catchment, by a single rain type on the whole surface. The sequences are 6 h sum of precipitations homogenous for the entire catchment. These 6 h cumulative rainfalls are compared at each time step with a threshold (e.g. the 2 yr return period 72 h rain).

When the 6 h sum of precipitations exceeds the threshold, a Nat Cat event is identified and created. Every event of the event set is simulated with the deterministic model to generate hazard maps and damages.

3.2.5 Combination of small scale watershed

Precipitations are generated on small catchments. In order to get precipitations for the entire French territory, we use a Gaussian copula to analyze the dependence between catchments. In our study, we want 72 h sliding cumulative sum of precipitation on each watershed. In our study, the 96 French departments (CRESTA zones) are considered as small catchments. A statistical analysis allows us to assume that the 72 h cumulative rain fields are temporally independent for each small catchment. We generate daily rainfalls and compute the cumulative sum for every 3 day. To preserve the seasonal pattern, a year of precipitations is simulated broken down into 4 parts corresponding to the 4 quarters of the year. We obtain, for each year, 122 sliding amounts of precipitations that preserve the observed correlation between watersheds.

With this method, for 5000 yr of continuous fictive 72 h rainfall, 8240 events are created. Each event in the library is simulated with the complete deterministic flood model to calculate its impact in terms of hazard and damages (Fig. 6). In this approach, the rainfall/runoff model used the simulated rain fields as the efficient rain. The initial soil moisture content is dependent on the month of occurrence and is calibrated on the observed values. For each event in the event set, the analysis of uncertainties in the damage distribution is calibrated on the simulation of the 1995–2010 historical event set. This probabilistic distribution is called *F2*.

3.3 Combination of *F1* and *F2* for exceedance probability mapping

The first and second approaches allow us to build 2 distributions of flood events. The probability of occurrence of each event is not calculated but every event is considered as unique in the distribution. It occurs only once in the total number of years simulated. These 2 distributions are not independent: small gauged river overflow may have been simulated with both methods. The *F1* distribution presents highest values for extreme river overflow events (e.g. Seine overflow in Paris, Rhône and Saône in Lyon, Garonne in Toulouse or Bordeaux). Nevertheless, for small river overflow, the *F1* approach underestimates the insurance losses: the surface water runoff damages will not be taken into account. For both reasons, *F1* and *F2* distributions must be combined to build a complete flood distribution. We propose the following method:

F1 is the annual loss distribution for the large catchment river overflow approach (1000 yr). *F2* is the annual loss distribution for the small catchment surface runoff approach (1000 yr). *S* is a given threshold, e.g. the maximum value observed for *F2*. The annual probability to exceed this threshold is estimated by:

$$P_{A>S} = \frac{n_{A>S}}{n} \tag{15}$$

where n and $n_{A>S}$ are respectively the total number of years and the number of years with a loss exceeding the threshold. We build F, an event set combining the entire *F2* distribution and the selection of $n_{A>S}$ most extreme years of *F1*. If $n_{A>S}$ is very small compared to *F2*, the probability (Eq. 16) will not be significantly different to Eq. (15).

$$P_{B>S} = \frac{n_{B>S}}{n + n_{A>S}} \tag{16}$$

Two hazard maps are created for each event in the event set: a river overflow map and a surface runoff map. The hazard maps are overlayed to construct a probabilistic hazard map indicating, at each point of the territory, the return period of a given hazard intensity. These maps correspond to the flood extent map according to the (de Moel et al., 2009) classification. The map shown on Fig. 2 is built for the following intensities: non-null water level for river overflow and a surface water runoff $> 5\,\mathrm{m}^3\,\mathrm{s}^{-1}$. The return period R indicated on the map is calculated as an exceedance probability:

$$R = \frac{N}{n} \tag{17}$$

where on each grid cell, n is the number of years with hazard intensity above the threshold and N is the total number of years in the simulation.

4 Results and discussion

4.1 Description of the stochastic event sets

The methodology chosen in this approach is to combine 2 independent event sets generated by 2 independent continuous simulations of hazard values: maximum monthly river flow for *F1* and cumulated 72 h rainfall for F2. The use of continuous hazard generation allows us to skip the calculation of a single event frequency.

An event set composed of 18 057 flood events has been generated with the *F1* model for 1000 yr of fictive river flows. These events are located on the entire French territory on the 7 major river catchments. The number of events per major catchment is: 3125 for Seine-Normandie, 4810 for Rhône-Méditerranée-Corse, 2786 for Adour-Garonne, 3149 for Loire, 1233 for Bretagne, 1540 for Rhin-Meuse and 1414 for Artois-Picardie.

Due to the selection of all river flow occurrences exceeding a return period threshold, the number of events is directly dependent on the number of gauge stations in each catchment. With this approach, 18 flood events per year occur on at least one river gauge on the French territory. These events have a minimum return period of 10 yr (the selected threshold for the study) and can be considered as Nat Cat events. In our approach, the different river flows generated on different flow gauges occur during the same month but not necessarily at the same time. The river flow values are propagated upstream and downstream until another gauge station with a generated value is present on a segment.

On the other hand, an event set composed of 8240 events has been generated by the rainfall generator and the *F2* model for 150 yr of fictive rain fields. These events are located on the 96 CRESTA zones over the French metropolitan territory. The number of events per catchment varies from 18 to 148 with an average value of 100 events. The average number of events per year for the *F2* distribution is 0.66 on a single catchment. For the entire French territory, 55 *F2* model events occur every year (8240 out of 150 yr). Based on these 150 yr of fictive rain fieds, the Copula method gives us 5000 yr of correlated 72 h rainfalls on the 96 CRESTA zones.

For the 2 methods (*F1* and *F2*), the hazard and damages are simulated with the deterministic model for each single event. For each event in the probabilistic event set, the damage distribution of uncertainties comes from the analysis of the deterministic approach on the 1995–2010 historical event set.

All the losses simulated for the events occurring during the same year are summed up to calculate the annual loss. For each year, within the *F1* method, the losses of the 12 months and the 7 major catchments are added. For *F2*, the losses of the 3-day events on the 96 catchments are added to compute the annual losses. We build 2 independent distributions of annua losses for flood. The *F1* only consider river overflow and the *F2* is a combination of small catchment river overflow and surface runoff due to heavy rainfall. The originality of this method is to combine both distributions considering independent years (*F1* years and *F2* years) to build a global flood loss distribution.

This method is applied on the calculation of annual flood losses for the insurance companies or for the whole insurance market. For this paper, we have chosen to calculate the flood losses for MACIF insurance.

4.2 Damage simulations for the MACIF insurance portfolio

MACIF, a French insurance mutual company has joined the CCR flood modeling project by providing high quality data of risks and claims. The MACIF portfolio is distributed homogeneously on the French territory. The non-motor Nat Cat premium for MACIF was 54.8 M € in 2011 which represents a market share of 4.6 % in France. MACIF is the first insurer for motor with a market share of 21 % and with a Nat Cat premium of 22.5 M €. As described in Table 2, the MACIF non-motor portfolio is composed of individual risks (93.8 %) and professional risks (6.2 %). In terms of Nat Cat premium, owners and tenants of flats are more represented in the MACIF's portfolio than in the Market's and, conversely, owners of individual houses are under-represented. These specificities will have an impact on the flood exposure. The 3 most represented types of risks in the MACIF portfolio (owners of individual houses, owners of flats and tenants of flats) will represent respectively 41.8 %, 1.3 % and 1.8 % of the total flood losses. The owners of individual risks concentrate the maximum losses for all perils and for flood (more than 65 % of the total losses) in the MACIF portfolio. With the owners of flats, over 80 % of the all perils and flood losses are represented. The amount of losses per risk category is almost the same for flood as for all perils, this with flood only representing 39.6 % of the Nat Cat losses over this period.

In this study, we focus on the individual risk category. On these risks, a statistical approach is more robust than on professional or industrial risks for 2 reasons: the homogeneity of the insured portfolio and the high number of records in the claim database. The flood claim database analysis show that the individual risks represent 54.1 % of the total flood losses. Among individual risks, houses represent 93.7 % of the losses and flats only 6.3 %. Among individual house risks, the owners represent 82.6 % of the losses. The ratio of industrial and commercial damages increases with the event loss amount.

The geocoding quality is described in Table 3. A majority of risks is successfully geocoded at the address precision (61.8 % of the individual risk premium) or at the center of the street precision (24.7 %). Only 13.5 % of the individual risk portfolio is not precisely located (town center precision).

The historical flood losses for the period 1996–2011 are estimated by MACIF and described on Table 4. The present value of all annual losses was calculated by applying (1) the monetary inflation and (2) the increase in the market share of the MACIF portfolio. The average annual loss is 21.4 M €, and the one-in-ten-years loss is estimated to 54.7 M €. Many flood events have occurred during this period: e.g. Rhône overflow in 2003, Argens floods in 2010 and 2011, Gard in 2002. But in terms of damages, extreme flood events on the most exposed territories have not yet occurred. All historical losses for the MACIF include professional risks. These annual losses must thus not be compared with the results of the probabilistic approach.

The results of the simulation of the MACIF portfolio for the combination of *F1* and *F2* are described in Table 5. The probabilistic flood modeling results (Table 5) are significantly higher than the historical flood losses, especially as the model was applied strictly on individual risks. The probabilistic average annual loss is strongly influenced by the extreme years in the distribution tail. For example, the 1000 yr return period event has a simulated loss of 834 M € for the individual risks in the MACIF portfolio which is very high. The extreme years are the occurrence of major floods in several major catchments with high level of exposed values. Indeed, the *F1* model simulates major river overflow in the most important cities: e.g. the Seine in Paris, the Rhône and Saône in Lyon, the Garonne in Toulouse and Bordeaux. The *F2* model simulates high losses for territory strongly exposed to heavy rainfall and surface water runoff, especially in the urbanized areas. The "cevenol type" events in the South–East of France are typically concerned by this approach which is adapted to small catchments and heavy rainfall in short timescales.

These results show the importance of the probabilistic modeling to estimate the financial exposure to floods. The analysis of the historical events underestimates the risk. A long sequence of fictive year has to be produced to take into account the combination of major events in several catchments during the same year. In this study, 1000 yr of fictive river flow and 5000 yr of fictive rainfall are used. This sequence has generated large annual losses but it will be necessary in the future to simulate a longer sequence.

4.3 Exceedance probability maps

4.3.1 The Argens downstream floodplain

The map on Fig. 2 represents the downstream Argens watershed, near the cities of Roquebrune-sur-Argens, Saint-Raphaël and Fréjus. This region has been chosen for its strong exposure to flash flood events: 2 major events occurred in the recent years. In June 2010 and in November 2011, the flashfloods of the Argens river and its tributaries account for respectively 550 and 250 M € insurance losses (CCR estimates in 2013). On the map of Fig. 2, the official flood-prone area (the highest known floods) is overlayed with the exceedance probability maps generated by the probabilistic flood model. The flood areas on the map are the Argens and tributaries floodplains (Reyran, Grande Garonne).

In the aggregate, the probabilistic river overflow fits with the official flood prone areas, especially for short return periods (< 50 yr). Nevertheless, the modeled flood zone covers a larger territory. On paper, the modeled flood zones could cover a larger expanse than the highest known floods. But, between two high return periods, e.g. 100 and 150 yr, there are only small differences between the levels of water (centimeter scale). The modeled flood zone should remain close to the highest known flood zone. Important differences are probably due to modeling uncertainties. The differences can be explained by uncertainties in the generated water level or in the elevation model (1 m elevation resolution).

The map of Fig. 2 reveals the important geographical exposure to the surface water runoff, for territories outside the Argens floodplain. For example, Saint-Raphaël, Boulouris-sur-mer, Saint-Aigulf, Les Issambres and the North-East of Fréjus.

To validate the model results, the historical flood claims, geocoded at the "street number" precision, have been overlayed with the official flood prone areas (Fig. 3) and the probabilistic flood map (Fig. 4).

Figure 3 show that many claims are located outside the floodplains. A large majority of flood claims in this region is concentrated in the urban centers, outside the flood zone. These claims account for 46 % of the total losses for this region. They represent 87 % by loss count. The first conclusion is that the most expensive claims are located in the floodplains, since 13 % of the data count for more than half the total losses. The river overflow inside the floodplains, in this region, explains only the half of global flood losses. Our assumptions is that surface runoff in the urbanized areas has generated these claims located outside the Argens major riverbed. The results of the probabilistic model will confirm this theory.

This confirms the importance of modeling the surface water runoff in a comprehensive complete flood model. On the map of Fig. 4, when combining river overflow with surface water runoff, a significantly higher ratio of claims (81 %) and losses (96 %) are located inside the flood areas. The remaining claims located outside the modeled flood areas can be explained by uncertainties in DEM elevation data coupled with uncertainties in the hazard model which are a subject for more investigations. For example the model does not take into account the sewer network and the risk of sewer overflow inside the urban areas. Furthermore, the model does not take into account the street network and its effect on the water velocity. The need to use a more precise DEM for elevation resolution (< 1 m) and spatial resolution (< 50 m) will enhance the simulation results. In the short term, a 5 m DEM will be used in the urbanized areas for rainfall/runoff and flood propagation computing. Some claims are also generated by other perils, such as seasurge and cannot be explained by river overflow and surface water runoff.

Counting the flood claims inside the flood areas is necessary but not sufficient for the validation of the flood model. If an urbanized area, located inside the flood zones, has never been concerned by any flood claim, either the possible flood has not yet occurred, or the flood zone is a model error.

The ratio of the number of claims to the number of insurance policies inside and outside the flood areas has been computed. This ratio is the so-called “claim frequency”. It is calculated at the level of the whole French metropolitan territory. The model is validated if the claim frequency is optimized inside the flood zones and minimized outside.

Inside the flood zone, we expect the modeled claim frequency to be close to the historical claim frequency which is usually between 1 and 10 % depending on the hazard intensity. Outside the flood zone, the claim frequency must be close to zero.

4.3.2 Metropolitan France probabilistic flood map

Figure 5 presents the results of the exceedance probability mapping for the whole French metropolitan territory and a focus on Île-de-France. At the French territory scale, 78 % of the flood claims are located inside the modeled areas whereas only 30 % inside the official flood prone areas. This result is confirmed by the claim frequency in the flood zone. The claim frequency inside and outside the flood areas are estimated respectively at 2.51 % and 0.12 %. Inside the flood zone, the claim frequency is in the range of 1 to 10 %. Outside the flood zone, the claim frequency is considered close to zero. These results allow the authors to validate, at the national scale, the exceedance probability mapping and the flood model.

The probabilistic flood map shown on Fig. 5 is the first flood map in France combining 2 perils: surface water runoff and river overflow at a national scale with a homogeneous method. The areas exposed to floods represent 52 374 km^2, i.e. 9.8 % of the French metropolitan territory. River overflow areas and surface water runoff account respectively for 6.1 % and 3.7 % of the metropolitan territory. The part of the territory exposed to < 50 yr, < 100 and > 100 yr return period flood is respectively 4.6 %, 5.4 % and 9.8 %. The surface water runoff exposed areas represent 30 to 40 % of the modeled flood areas, depending on the return period.

These probabilistic flood maps have been used to determine the exposure to floods for insurance company portfolios and for CCR as a whole. On each point of the territory, the intensity/return period curve can be obtained and used for cost/benefit analyses.

4.4 Limits of the method

This approach is a large scale simulation method. It combines many uncertainties in the hazard model, in the vulnerability and damage model. In the hazard model, major sources of uncertainties are due to DEM elevation precision (1 m) and spatial precision (50 m), lack of knowledge on river characteristics (precise width, flow gauges network), lack of knowledge on the flood protections (for overflow threshold) and sewer network influence along with street mapping on the rainfall/runoff model. Nevertheless, the hazard model is validated by comparison with the historical river flow (banque Hydro) or with available satellite images of the flooded area, for the historical event set. Whilst not shown in this paper these results constitute the main calibration of the deterministic hydrological modeling.

The uncertainties in the vulnerability and damage models come from the lack of precision in the address location of the insurance policies and risks, the estimation of the insured values for the different types of risks (individual, commercial, agricultural) can be an important source of uncertainties if not present in the insurance database. Furthermore, in the claim database, the lack of major industrial claim data makes it difficult to calibrate a damage model for these risks, and thus the statistical approach for industrial risks reaches its limits. Here again, this model is calibrated on the historical event set. Comparison is made, for every change in the hazard or damage model, with the historical losses and the calculation of the global error of the model. Every choice that has been made on the development of our model has improved the event loss simulation results. If it is not the case, the modification of the model is not maintained.

The works of (Apel et al., 2009) on the details needed for a hazard and damage modeling in an urban area are, in our context, really appropriated. We use a detailed modeling for damage (at the risk level) and a meso-detailed hazard modeling (simplified rainfall/runoff combined with a simplified hydrological routing model). Further investigations have been made by CCR by using a meso-scale damage level (repartition of insured risks in the land cover areas inside the commune level) and the first results are, at least for the individual risks, not significant changes in the event losses. These works would confirm the need to have a good combination of detail for hazard and damage models. For industrial locations, the need to have the latitude/longitude location of the risk is important, since these risks are not numerous, the uncertainties in their location is not compensated by their spatial distribution on the event area. For these risks, taking into account the flood duration modeled as an input data for the damage model would permit the estimation of a business interruption.

5 Conclusions

The objective of this study is to estimate the financial exposure to flood for the French insurance market. 2 perils represent the major part of the flood losses in France: river overflow and surface water runoff due to heavy rainfall, particularly in the southern regions. In France, the official flood prone areas are heterogeneous and only cover a single peril: river overflow. Furthermore, these areas have no intensity or frequency information. To estimate the exposure to flood, a probabilistic model combining river overflow and surface water runoff is built. This probabilistic model is based (1) on a deterministic flood model which simulates hazard, vulnerability and damages, calibrated on the historical claim database and (2) on a combined event set. This stochastic event set combines a river flow database with a rain field database to simulate the flood events. The results of this probabilistic flood model are studied on the MACIF portfolio, a French insurance company and specifically on the individual risk types. The average and extreme annual flood losses are calculated. The first multi-peril exceedance probability flood map for the entire French territory, combining river overflow and surface water runoff with an homogeneous approach, is published on this paper. A focus on the Argens watershed to understand the model validation is described.

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References

Aon Benfield, A. (Ed.): January 2013: Global Catastrophe Recap, Impact Forecasting, 2013.

Apel, H., Aronica, T., Kreibich, H., and Thieken, A. H.: Flood risk analyses - how detailed do we need to be? Nat. Hazards, 49, 79–98, 2009.

Arnaud, P. and Lavabre, J.: Estimation de l'aléa Pluvial en France Métropolitaine, Guide Pratique, Editions QUAE, 2010.

Banque Hydro: Banque nationale de données pour l'hydrométrie et l'hydrologie, Ministère de l'Environnement et du Développement Durable, Paris available at: http://www.hydro.eaufrance.fr/accueil.html (last access: 8 July 2013), 2006.

Bates, B. C., Kundzewicz, Z. W., Wu, S., and Palutikof, J. P. (Eds.): Climate change and water, Technical paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, 210, 2008.

Bradbook, K., Waller, S., and Morris, D.: National floodplain mapping: datasets and methods – 160,000 km in 12 months, Nat. Hazards, 36, 103–123, 2005.

de Moel, H., van Alphen, J., and Aerts, J. C. J. H.: Flood maps in Europe – methods, availability and use, Nat. Hazards Earth Syst. Sci., 9, 289–301, doi:10.5194/nhess-9-289-2009, 2009.

Dráb, A. and Říha, J.: An approach to the implementation of European Directive 2007/60/EC on flood risk management in the Czech Republic, Nat. Hazards Earth Syst. Sci., 10, 1977–1987, doi:10.5194/nhess-10-1977-2010, 2010.

Durand, Y., Brun, E., Merindol, L., Guyomarc'h G., Lesaffre, B., and Martin, E.: A meteorological estimation of relevant parameters for snow models, Ann. Glaciol., 18, 65–71, 1993.

EXCIMAP (European Exchange Circle on Flood Mapping): Handbook on Good Practice on Flood Mapping in Europe, available at: http://floods.jrc.ec.europa.eu/flood-risk/excimap-handbook-on-flood-mapping (last access: 8 July 2013), 2007

Falter, D., Vorogushyn, S., Lhomme, J., Appel, H., Gouldby, and Merz, B.: Hydraulic model evaluation for large-scale floor risk management, Hydrol. Process., 27, 9, 1331–1340, 2013.

Green, W. H. and Ampt, G.,: Studies of soil physics part I – the flow of air and water through soils, J. Agr. Sci., 4, 1–24, 1911.

Jongman, B., Kreibich, H., Apel, H., Barredo, J. I., Bates, P. D., Feyen, L., Gericke, A., Neal, J., Aerts, J. C. J. H., and Ward, P. J.: Comparative flood damage model assessment: towards a European approach, Nat. Hazards Earth Syst. Sci., 12, 3733–3752, doi:10.5194/nhess-12-3733-2012, 2012.

Krige, D. G.: A statistical approach to some basic mine valuation problems on the Witwaterstand, Journal of Chemical, Mettalurgical and Mining Society of South Africa, 52, 119–139, 1951.

Kohonen, T.: Self-Organizing Maps, vol. 30, Springer Verlag, 1995.

Leblois, E. and Creutin, J.-D.: Space-time simulation of intermittent rainfall with prescribed advection field: adaptation of the turning band method, Water Resour. Res., 49, doi:10.1002/wrcr.20190, 2013.

Legifrance.gouv.fr (Ed.): Loi n°82–600 du 13 juillet 1982 relative à l'indemnisation des victimes de catastrophes naturelles, 1982.

Manning, R.: On the flow of water in open channels and pipes, Transactions, Inst. Civ. Eng. Ireland, 20, 161–207, 1891.

Matheron, G.: The intrinsic random functions and their applications, Advanced Applied Probability, 5, 439–468, 1973.

Messner, F., PenningRowsell, E. C., Green, C., Meyer, V., Tunstall, S. M., and van der Veen, A.: Evaluating flood damages: guidance and recommendations on principles and methods, FLOODsite, Wallingford, UK, T09–06-01, 2007.

Moncoulon, D. and Quantin, A.: Modélisation des Événements Extrêmes d'Inondation en France Métropolitaine, La Houille Blanche, Revue Internationale de l'Eau, 1, 22–26, 1, 2013.

Nelsen, R. B.: An Introduction to Copulas, Lectures Notes in Statistics, 139, Springer Verlag, New York, 1999.

Poulard, C. and Leblois, E.: Towards objective design of dry dams at watershed scale: how to take into account the spatial structure of the rainfall and its variability. Proceedings: hydrological extremes in small basins, 12th Biennal International Conference of the Euromediterranean Network of Experimental and Representative Basins (ERB), Krakow, Poland, 18–20 September 2008, available at: http://unesdoc.unesco.org/images/0018/001828/182846e.pdf, last access: 8 July 2013.

Quantin, A.: Modélisation du péril inondation: passage d'une approche déterministe à une approche probabiliste en vue d'une tarification à l'exposition des couvertures de réassurance dans le cadre du régime des Catastrophes Naturelles, Rapport confidentiel, Mémoire d'actuaire, Centre d'Etudes Actuarielles, 164, 2011.

Sklar, A.: Fonctions de Répartition à n Dimensions et leurs Marges, Publications de l'Institut de Statistique de Paris, 8, 229–231, 1959.

Swiss Re: Flood – an Underestimated Risk, Inspect, inform, insure, Swiss Re Productions, Zurich, 2012.

Table 1. Sources and description of the main input data for the hazard and damage model (deterministic and probabilistic models).

Input data	Source	Description
Digital elevation model (DEM)	IGN BD Alti	DEM with 1 m resolution on a 50 m × 50 m grid covering the French metropolitan territory
River database	IGN BD Carthage 2012	Selection of 65 000 km of river out of 315 000 km
Measured rainfall data	Météo-France Publithèque	Rain gauges stations
Evapotranspiration	Météo-France Publithèque	Penman model applied by Météo-France on rain gauge stations
Modeled rainfall data	Météo-France SAFRAN database	51 yr of hourly and daily precipitations on a 8 km × 8 km grid
Hydrological data	SCHAPI – Ministry of environment	Historical water level measurements on Banque Hydro river gauges
River protections against flood	CCR	Determination of flood threshold by comparing Nat Cat decrees per commune wih historical river flows
Policies and risks locations, insured values and lines of business	CCR insurance database	The database content is estimated as 70 % of market share for 2011 portfolio
Natural Disaster claims	CCR insurance database	The database content is estimated as 50 % of market share for 2011 portfolio
Natural Disaster recognition per commune	CCR Nat Cat database	Exhaustive database since 1982 for all Nat Cat decrees
Destruction rate curves	CCR	Calibrated on CCR claim database and hazard model outputs

Table 2. Composition of MACIF insurance portfolio and comparison with the global insurance market portfolio, for individual risks, in terms of Nat Cat premium.

Portfolio	MACIF		MARKET		DIFF (%)
Nature of individual risks	Nat Cat premium (€)	%	Nat Cat premium (€)	%	
Owners of individual houses	21 898 147	42.6	345 859 040	55	−12.4
Tenants of individual houses	3 387 674	6.6	44 738 035	7.2	−0.6
Owners of flats	10 579 481	20.6	64 471 531	10.3	10.3
Tenants of flats	11 153 206	21.7	120 340 637	19.28	2.42
Others	4 362 115	8.5	48 635 606	7.7	0.8
Total individual	51 380 626	100	624 044 849	100	

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Table 3. Geocoding quality of MACIF individual risk portfolio 2011.

Geocoding results for individual risks	Total premium (€)	% of global portfolio
Adress	31 737 933	61.8
Street center	12 682 551	24.7
Town center	6 951 406	13.5
Fail	8738	0

Table 4. MACIF historical flood losses on the period 1996–2011.

Flood losses	Annual flood losses (€ 2011)
Mean	21.4 M €
10 yr return period	54.7 M €
Maximum	61.5 M €

Table 5. Description of the *F1* and *F2* model results: per event and annual loss distributions (million €) for individual risks for the MACIF portfolio.

Losses	Per Event		Annual
Distribution parameters	*F1* model	*F2* model	Combined *F1* and *F2* models
Mean	7.4	0.5	46.3
90th percentile	19.1	1.3	78.4
99.9th percentile	258.5	34.7	834.5

Table 6. Deterministic model results in a selection of historical flood event set. These model results are compared with the CCR estimations for the event losses (million €). These estimations are based on the extrapolation of insurance claims.

Losses Historical events	Simulated Inf.	 Sup.	Historical Best estimate
South east Sep 2009	48.4	66.4	53.6
Center-east Nov 2008	94.3	171.3	125.6
Rhône-Alpes storms Sep 2008	45.3	85.0	41.8
South west storms May 2007	4.1	11.4	19.4
Meurthe-et-Moselle Oct 2010	25.6	59.7	51.5
Gard Sep, 2005	120.1	277.6	83.8
Arles and Rhône Dec 2003	422.4	964.9	834.4
Gard Sep 2002	297.2	600.5	609.1

Table 7. Loss distribution for an historical event (south-east in september 2009) simulated with the deterministic model for the insurance market (in million €). The error distribution is calibrated on a selection of the 1995–2010 event set by comparing modeled losses with real claims.

Modeled loss distribution	10th perc.	30th perc.	70th perc.	90th perc.
Historical event South-east Sep 2009	40.6	48.4	66.4	93.6

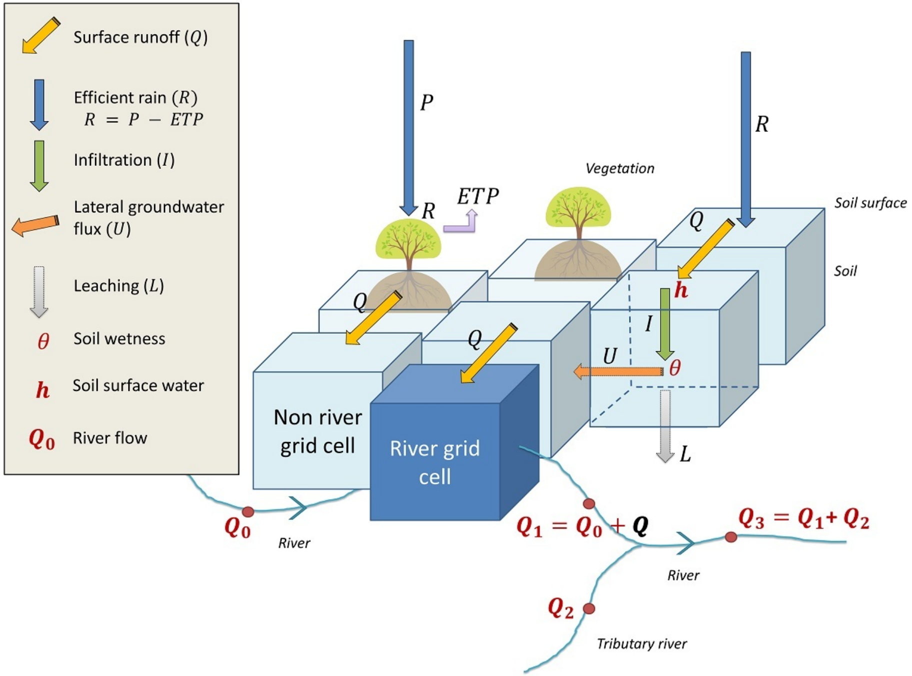

Fig. 1. Runoff/rainfall and river routage processes for the distributed hazard model used for the deterministic and probabilistic approaches.

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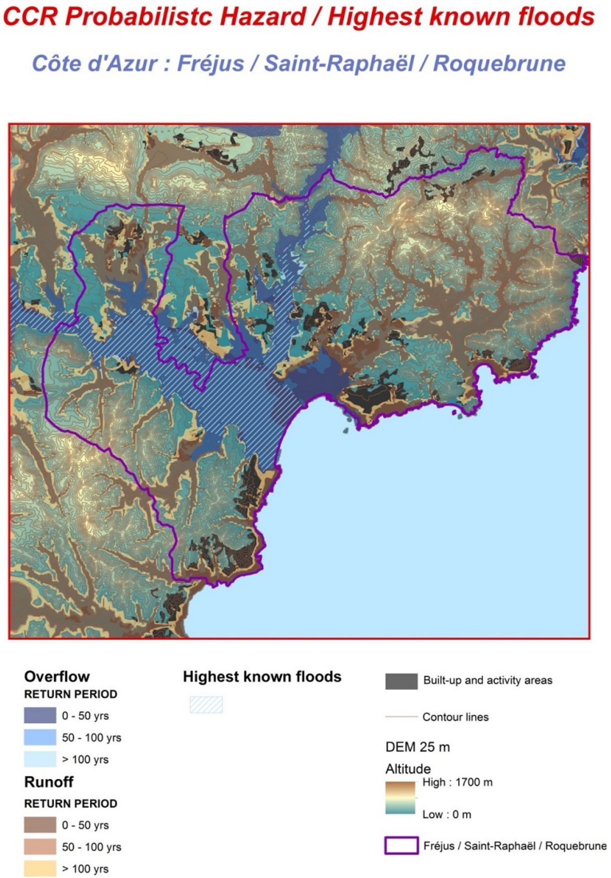

Fig. 2. Probabilistic flood map and official flood prone areas on the downstream floodplain of the Argens river near Fréjus, Saint-Raphaël and Roquebrune. This exceedance probability map combines the Argens overflow area with the surface runoff at different return periods.

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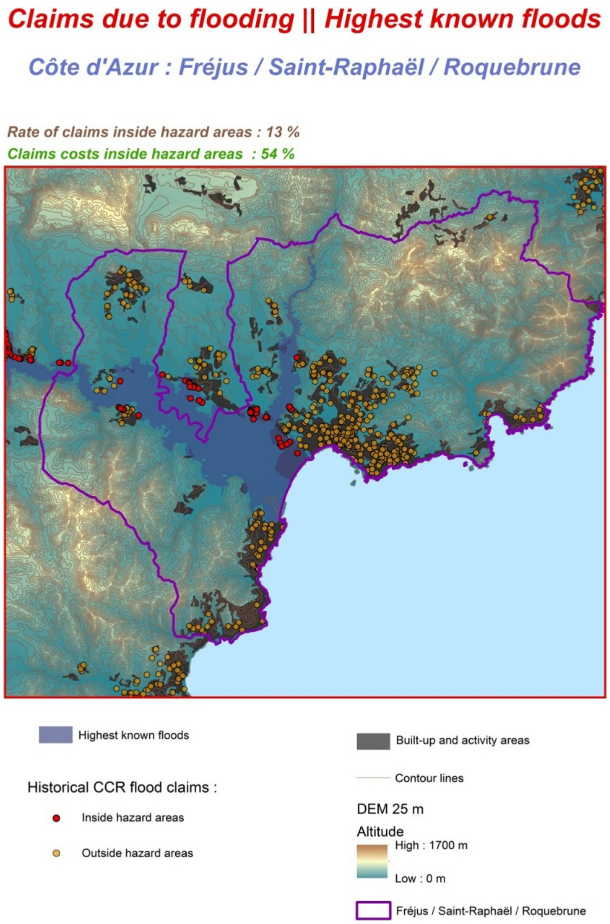

Fig. 3. Official flood prone areas (highest known water level) map overlayed with adress-precision geocoded market claim data. Focus on the downstream floodplain of the Argens river near Fréjus, Saint-Raphaël and Roquebrune.

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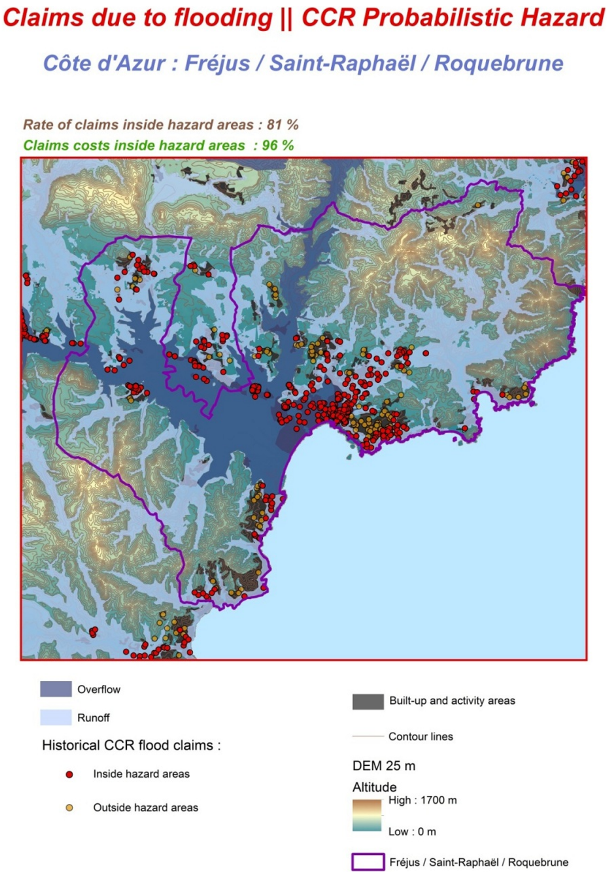

Fig. 4. Exceedance probability map overlayed with adress-precision geocoded market claim data. Focus on the downstream floodplain of the Argens river near Fréjus, Saint-Raphaël and Roquebrune.

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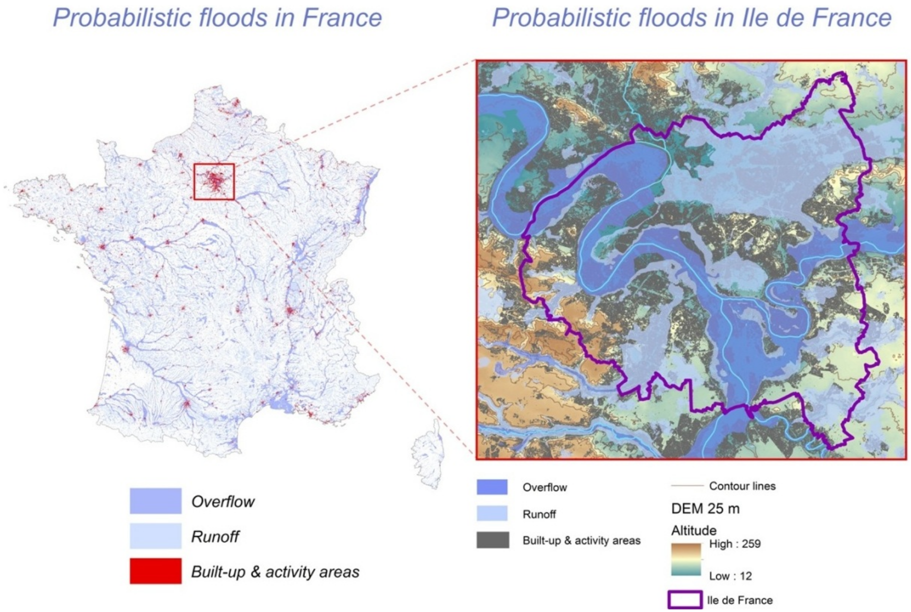

Fig. 5. Exceedance probability map for the French territory combining the river overflow and the surface water runoff. This map is overlayed with the build-up and activity areas. A focus on Île-de-France overlayed with a 25 m DEM is displayed.

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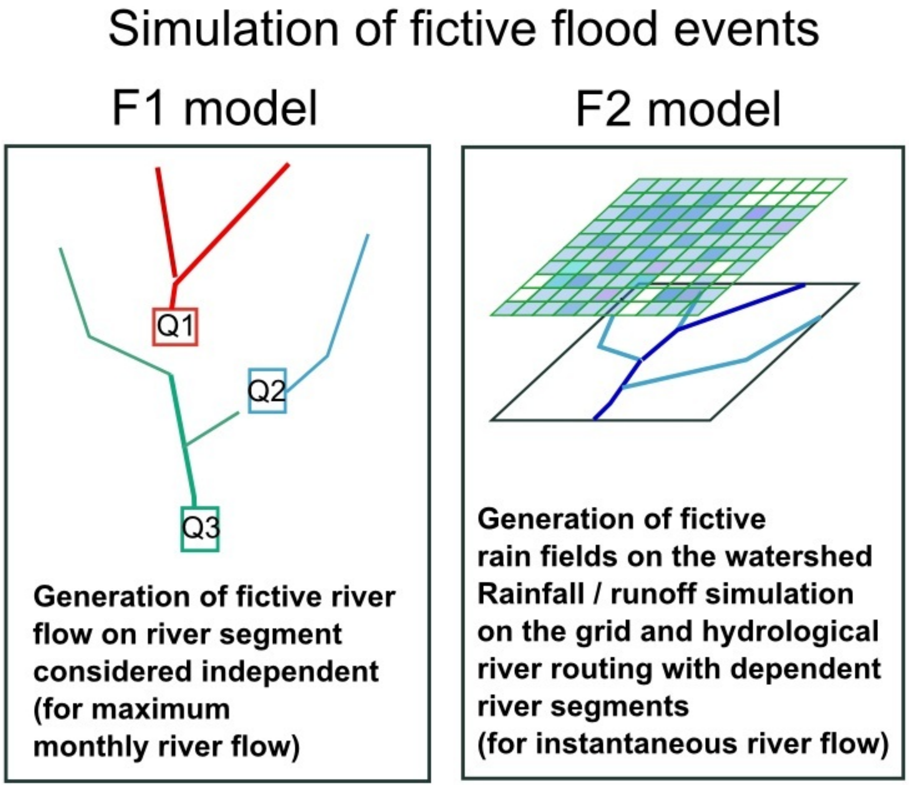

Generation of fictive river flow on river segment considered independent (for maximum monthly river flow)

Generation of fictive rain fields on the watershed Rainfall / runoff simulation on the grid and hydrological river routing with dependent river segments (for instantaneous river flow)

Fig. 6. Hydrological method to simulate river flow. Comparison between *F1* and *F2* model on a fictive small river catchment.

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