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Discussions

Estimation of insurance related losses resulting from coastal flooding in France

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Abstract

A model has been developed in order to estimate insurance-related losses caused by coastal flooding in France. The deterministic part of the model aims at identifying the potentially flood-impacted sectors and the subsequent insured losses a few days after the occurrence of a storm surge event on any part of the French coast. This deterministic component is a combination of three models: a hazard model, a vulnerability model and a damage model. The first model uses the PREVIMER system to estimate the water level along the coast. A storage-cell flood model propagates these water levels over the land and thus determines the probable inundated areas. The vulnerability model, for its part, is derived from the insurance schedules and claims database; combining information such as risk type, class of business and insured values. The outcome of the vulnerability and hazard models are then combined with the damage model to estimate the event damage and potential insured losses. This system shows satisfactory results in the estimation of the magnitude of the known losses related to the flood caused by the Xynthia storm. However, it also appears very sensitive to the water height estimated during the flood period, conditioned by the junction between sea water levels and coastal topography for which the accuracy is still limited in the system.

1 Introduction

The Xynthia storm, which occurred in France in February 2010, renewed the awareness of coastal flooding risk on the French coast (Lumbroso and Vinet, 2011). This peril, resulting from the combination of high spring tide and extreme meteorological conditions, leads to very high levels of loss; both in term of death and injury and in resultant economic losses. The financial cost of Xynthia has been estimated to have been approximately EUR 2.5 billion, of which EUR 1.5 billion was covered by insurance and reinsurance companies (FFSA and GEMA, 2011). In terms of insurance payments, Xynthia is one of the most costly storm events to have occurred in France in the last thirty years.

In France, the financial compensation for the victims of such natural disasters is governed by the national Natural Catastrophes system (thereafter the Nat Cat-system). This has provided approximately EUR 830 million for the victims of Xynthia. This system engages CCR (Caisse Centrale de Réassurance) a reinsurance company, which is owned by the French State, to administer the state guaranty for Nat Cat events.

In order to meet the needs of the French State and its clients, and for its own income forecasts, CCR has developed models aiming to estimate the insured losses arising out of Nat Cat events (flood, coastal flooding, windstorm, drought, earthquake and volcanic eruption). The strategy of CCR is to develop its own modelling tools for natural disasters in order to have control over the different components of the model and to validate them with the available data. The development of such models is also made possible by the significant database of insurance schedules and claims that have been collated by CCR with the support of its cedants (cedant – this term designates the client companies of CCR).

Coastal flooding modelling faces several issues: scales (multi frequency and multi spatial scales processes); process interaction related to the forcing conditions (waves, surge, tide, river discharge etc.); coastal flooding process complexity (overtopping, interaction with structures, etc.); a detailed enough knowledge of the topography and associated structures. Several approaches have been developed to estimate coastal flooding, ranging from the simple approach of estimating flooding from topographic contours to the more accurate 2-D/3-D, time-varying, full-process models. Estimating flooding from topographic contours leads to an overestimation of the flood event, without providing any information on the velocity or the temporal dynamics (e.g., Breilh et al., 2012). In the case of the 2-D/3-D process-based models, they have a typical grid resolution of 10–20 m and use empirical formulae to take into account wave overtopping processes. As a consequence, they do not enable a realistic representation of the water height and flows in urban areas. Recent modelling developments now permits realistic 2-D simulations of urban areas conditions (Le Roy et al., 2014), but still with computation time exceeding several days to simulate a few event hours, even on multi-processor clusters. To tackle the issue of estimating coastal flooding on a national scale, a compromise has to be found between the quality of the results, feasibility (data available) and computational time. This leads to the necessity of developing alternative approaches, between those of basic static projection of water levels and the most advanced approaches used for projecting events in urban areas.

The requirements of CCR correspond to two objectives. The first is to determine the likely affected areas and the resultant cost of catastrophic events a few days after their occurrence. This estimation allows CCR to advise the French State and its clients of the potential financial magnitude of the event. The second objective is to assess the potential losses due to extreme events according to their return period. Successful achievement of this objective will allow effective evaluation of the financial exposure of CCR, the French State and of cedants to coastal flooding risk.

In order to fulfil the first objective for storm surge projection, a deterministic model is currently being developed by CCR. Numerous studies have been published on the estimation of flood damages (Jongman et al., 2012; Messner et al., 2007; Meyer and Messner, 2005). Generally, these models combine a hazard model which characterizes the intensity of the event, and a susceptibility model, describing the exposure of the subject area and a damage model to estimate the financial cost. In the same way, some specific models for storm surge have been developed, especially for tropical cyclones in America (Genovese et al., 2011; Wang et al., 2014) or in the Netherlands-dealing with the problematic nature of polder areas (de Moel et al., 2012; Bouwer et al., 2009). These models are most often concerned with the global economic cost, but some more specific works have concentrated on the insurance cost. For example, Pistrika and Jonkman (2009) have studied the insurance cost due to hurricane Katrina. Sousounis and Kafali (2010) in a recent study have used the AIR model to estimate the potential cost of the 1959 typhoon in Japan. Some models use a probabilistic approach, like Gaslikova et al. (2011) for consideration of future storm surge impact in the North Sea region. The approach of Czajkowski et al. (2013) presents a methodology to determine premium on the basis of property exposure to coastal flood risk.

For CCR, the loss consideration will not concern itself with damage to public infrastructure or assets or agricultural losses as these are not included in the Nat Cat compensation system. Thus, a specific calibration is needed such as it has already been established for inundation by CCR (Moncoulon and Quantin, 2013; Moncoulon et al., 2014).

In order to estimate the losses related to coastal flooding events, the deterministic model has been developed on the same structure followed by most of the insurance related catastrophe models: a hazard model, a vulnerability model and a damage (financial loss) model. This development should face two main challenges. The first one is the operational modelling of the inundation resulting from coastal flooding hazard at a large scale (the French coasts) and within a short time-frame and the second consideration integrates the hydrodynamics output and the limitations of the insurance related data.

The present paper examines the methodology developed for a timely estimation of the costs generated by coastal flooding: a hazard model is used to estimate flooded areas, and a vulnerability model then allows estimation of the exposure of insurance policies to coastal flooding, before finally calculating the potential cost of the event through a damage model. This methodology has been applied to the data relating to the major coastal flooding that occurred during Xynthia storm in France in 2010. A sensitivity analysis has permitted a full understanding of the effectiveness of the hazard model in interpreting/predicting the results, and permitted the application of the methodology to four other minor events shows the consistency of the results.

2 Hazard model

2.1 Methodology

The purpose of the hazard model is to estimate the water levels over the land areas where there is likely to be insurance policy coverage. During a storm event, water levels along the coastline are influenced by three main processes. The first one is that of tide variation, which plays an important role along the Atlantic coast of France, the Channel and the North Sea. The amplitude can vary from 3 to 11 m for spring tides (SHOM, 2012). The second process is atmospheric storm surge, resulting essentially from atmospheric pressure and wind effect, and its coincidence with high tides. For Xynthia, this surge was estimated to have been 1.5 m at La Rochelle (Bertin et al., 2012).

In this study, we chose to use the Previmer system (www.previmer.org) to determine potential water levels resulting from these two processes. This system provides both forecasts and observations of water levels, but also models waves, currents, temperatures and plankton content.

The third component is the wave setup which corresponds to the surge that is generated by the wave breaking over the beach. This surge component, not provided within the Previmer, model, could represent a significant part of the total surge effect (Dean and Walton, 2008) and is estimated on the basis of the wave characteristics.

Once the total water levels have been estimated along the coastline, an inundation model propagates them over the landmass behind. For this purpose, an inundation model, similar to the Lisflood-FP model (Bates et al., 2010) is utilized. Finally, this modelling chain allows estimation of the inundation process by assessing the volume of the overflowing seawater, but this is projected without the additional consideration of the consequences of wave overtopping or the destruction of sea defenses.

We consider the specifics of each of the hazard module components below.

2.1.1 Tide, atmospheric storm surge and regional wave setup

In France, the Previmer system, created in 2006 (Lecornu and De Roeck, 2009), provides forecasts of currents, water levels or atmospheric surges for the mainland. This system uses the MARS-2-D hydrodynamic model (Lazure and Dumas, 2008) and usually shows satisfactory results (Idier et al., 2012; Pineau-Guillou et al., 2012). The model is based on the resolution of shallow-water equations with the finite difference method. The model runs on three different levels of resolution: 2 km for the North East part of the Atlantic Ocean, 700 m for the Channel and the Bay of Biscay and 250 m for five smaller areas. The bathymetry used by Previmer is based on the NOOS 1° (North-West Shelf Operational Oceanographic System), EMODNET (European Marine Observation and Data Network) and the SHOM-Ifremer DTM at 100 and 500 m of resolution. The MARS-2D model uses the FES2004 tide model (Lyard et al., 2006) for the two lowest resolutions and the model cstFrance (Le Roy and Simon, 2003) with 115 harmonic constants at 250 m. The meteorological data is provided by Meteo France and is based on Arpege (Courtier et al., 1994) and Arome models (Seity et al., 2011) according to the resolution level.

The validation of the model, realized by Pineau-Guillou (2013) on the basis of water levels simulated, has shown that root mean square errors (RMSE) are usually comprised between 9 and 17 cm, with a mean of 13 cm, which is deemed to be satisfactory. However, these errors can be higher for exceptional events such as Xynthia. The difficulties of generating an effective estimation of the inundated areas for Xynthia could be explained by the fact that this event had characteristics which were quite particular. Indeed, Bertin et al. (2012) have shown that the associated surge was exceptionally high for this event in comparison to the intensity of the storm. This behavior could be explained by the trajectory of the depression that induced an Ekman transport directed toward the coast, enhanced by the presence of young and steep waves (Bertin et al., 2014). Thus, the version of Previmer used in this study tends to underestimate water levels observed in the central part of the Bay of Biscay during the Xynthia event. This underestimation could reach 30 to 40 cm in some sectors. In order to use the Previmer outputs in the best conditions for our system, the water levels simulated have been adjusted to match the highest levels observed by tide stations during the simulated events. It should be noted that tide gauge measurements include tide and atmospheric storm surge, but also regional wave setups. Indeed, for instance at La Rochelle, as shown by Bertin et al. (2015), the total water level result from these processes, with a regional wave setup, was between 5 and 10 cm at La Rochelle. Thus, our calibration method indirectly permits the taking into account not only tide and atmospheric surge, but also the regional wave setup. An illustration of two maregraphs obtained for Xynthia is presented for in Fig. 1 and shows that RMSE were generally between 10 and 30 cm for this event.

2.1.2 Wave setup

Waves could also play a key role in the inundation processes during storm surges with the phenomena of wave setup and wave runup (Kim et al., 2008; Ferrarin et al., 2013). However, it is relatively difficult to estimate these parameters accurately, especially on a large scale and with a poor bathymetry. In addition, as discussed in the water level calibration step, two kinds of wave setup can be identified. Regional wave setup, occurring over large areas such as bays (see e.g. Bertin et al., 2015) – which can be reproduced utilizing a rather coarse grid (e.g. 50 m grid size), and local wave setup, resulting from localized waves breaking near the coast, requiring usually finer grids (5–10 m grid size). As discussed in the above, the regional setup, even if not actually calculated here, has been indirectly integrated into the adjustment of the simulated water levels against the actual water levels observed by the tide stations, which are included in this regional setup model. Thus the values of the local wave setup, given as η are estimated within the empirical formula of Stockdon et al. (2006):

$$\langle \eta \rangle = 0.35\beta_{\mathrm{f}}(H_0 L_0)^{1/2}. \tag{1}$$

The parameters of this formula (the deep water wavelength L_0 and the significant wave height H_0), are computed using PREVIMER wave data (Ardhuin et al., 2010). The third parameter, representing the beach steepness $\hat{a}_f$ was estimated on the basis of the BD CARTO (IGN database). This database contains the limits of the low and high spring tide. The distance and the height between them are used to roughly estimate the beach slope. In order to measure and compare offshore parameters and those for beaches, vectors for the coastline were established every 250 m and a cross-section was established to determine the coordinates of the parameters. A selection of these cross-sections was then scrutinized: the sections for which the bathymetry did not reach a 20 m depth within a 5 km range offshore were deleted from the wave setup computation. In the same ways, in harbours, the cross sections have been deleted and instead the statistical setup of the surrounding beaches is applied.

Figure 2 shows the maximal wave setup height computed for the Xynthia event along the coast. The mean height often reaches 40 cm but extends to 80 cm for the most exposed areas. This empirical estimation of the local wave setup provides results of the same order as those obtained by Bertin et al. (2015) with spectral wave model results (local wave setup can locally exceed 0.4 m, even if the calculation resolution remains too coarse to capture the maximum setup along the coastline). These values justified the necessity of taking this phenomenon into account. However, the methodology actually presents two main limitations as it does not take into account wave refraction and shoaling effects and local wave setups that could impact sheltered bays. However, as explained above, the regional wave setup is indirectly taken into account, such that the wave setup along sheltered bays is not nullified. The potential impact of these limitations will be discussed in Sect. 4.3.

2.1.3 Coastal flooding model

Water levels estimated along the coastline are then propagated onto the land using an inundation model. Given the large scale and the operational aspects of the study, an application of full-process based model (for example based on non-linear shallow water equations or on Boussinesq equations) would have been too cumbersome to implement given the need for extensive spatial information and significant computational times required. As a result, a storage-cell flooding model has instead been used, similar to the Lisflood-FP model (Horritt and Bates, 2001; Hunter et al., 2005; Bates et al., 2010) that has been tested for the computation of coastal flooding by Bates et al. (2005) with good results. The model developed in this study is based on the continuity equation relating to flow and volume changes:

$$\frac{\partial h^{i,j}}{\partial t} = \frac{Q_x^{i-1,j} - Q_x^{i,j} + Q_y^{i,j-1} - Q_y^{i,j}}{\Delta x \Delta y}. \tag{2}$$

Where, $Q^{i,j}$ represents the flows ($\mathrm{m^3\,s^{-1}}$) between cells at the node (i, j), x stands for horizontal and y for vertical flows, Δx and Δy are the cell dimensions (m), h is the free water surface and t is the time (s). The flows between cells are estimated according to Manning Striker law with, for example in the x direction:

$$Q_x^{i,j} = \frac{1}{n}\left(h_{\mathrm{fmax}} - z_{\mathrm{max}}\right)^{5/3}\left(\frac{h^{i-1,j} - h^{i,j}}{\Delta x}\right)^{1/2}\Delta y. \tag{3}$$

Where n is the Manning's friction coefficient, h_{fmax} the highest water free surface in the two cells, and z_{max} the higher bed elevation.

The Digital Terrain Model (DTM) used for this study is a commercial DTM that presents a spatial resolution of 25 m. In order to apply the model within operational perspectives, the French coast has been divided into 39 sectors, exempted from interdependency, where the model is applied independently.

In order to take into account the roughness of the ground, the Manning's coefficient (n) is fixed according to the land use described in the Corine Land Cover database (2006), using the coefficients proposed by Lopes et al. (2013) for the Ria de Aveio at Portugal.

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Finally, the modelling process permits a chronological estimation of water levels for each cell of the DTM. Accordingly it is possible to extract, for each cell, the highest free surface water height presented by the damage model. This storage-cell model presents the dual advantages of being easy to set up and is relatively fast in computational time.

2.2 Results

After the Xynthia storm, inventories of inundated areas have been achieved. These inventories have been used in our study to compare the simulated flood areas and the observed inundated areas. The results of this comparison, presented for the Charente Maritime department in Fig. 3, show that the hazard model allows globally a good representation of the inundated areas with significant differences at the local scale: the CCR model makes projections of an inundated area of 670 against 595 km^2 actually affected.

There are, however, notable differences to be observed on the local area modelling. For example, there is the case of the municipality of Charron or that of Saint Pierre d'Oléron where the extent of the inundation is widely underestimated. These deviations could be due to underestimation of sea water levels in sheltered bays, but perhaps mainly by the quality of the DTM used. Indeed, at 25 m of resolution, dikes and protection walls have been smoothed, despite some corrections, and this could skew the real water level estimation. The quality of the DTM will be discussed in Sect. 3.2. In such flatlands, a few centimetre differences in water levels induce very different estimations of the inundated areas (see Sect. 4.3). It appears also that the quality of the meteorological data used by Previmer in 2010 was limited – there is a resolution of 0.5° and a time step of 6 h (Arpege model). Since 2012, the Previmer system uses Arome meteorological data with hourly time steps and a spatial resolution of 0.1°. This difference of the qualitative information explains why Previmer outputs underestimate water levels for the Xynthia event, in particular for bays such as the Aiguillon Bay where water levels are underestimated by about 40 cm. This deviation constitutes the main reason of the whole underestimation of the inundation spread for the Charron commune.

There are contrary cases where the model seems to overestimate flooded areas as, for example, in the Isle de Ré or Isle de Noirmoutier. The consequences are opposite, but the origins of the problem could be the same: the approximate estimation of water levels in the sea and the quality of the DTM used.

The results illustrate also an incorrect reproduction of the behaviour of inundation processes along the coastal inlets and estuaries. This is noticeable for the municipality of Rochefort for example where the inundation has been induced by the interaction between the river flow and the sea. This problem is not yet fully remedied in the actual version of the inundation model, but when so, this should probably improve substantially the results. Apart from in these areas, the model, even if basic, generally provides flooded areas being in a reasonable agreement with the observed ones.

3 Vulnerability model and hazard validation

3.1 Vulnerability database

The vulnerability model developed by CCR is derived from schedule information and loss records termed henceforth "insurance policies". A database was created under the framework of bilateral contracts with insurance companies under conditions of confidentiality. The fact that CCR provides cover for a very large proportion of individual French insurance policies offers a particularly broad vision of French exposure to coastal flooding risks.

This database describes the nature of the risk (house, building or apartment), its usage (residential or commercial) and its occupation (owner, tenant, co-ownership). For a large part of them, these risks have been geo-referenced. The latitude and the longitude are estimated on the basis of the location of the address in the street and not the real location of the building. Its real position could vary from a few meters to several thousand in some cases. In some cases, data sources do not permit a specific designation of the property locus, and the nearest co-ordinate-street or commune centre has therefore been adopted. Some complementary elements have been extracted from a DTM such as the distance to the coastline or the location elevation.

Additionally, each year, the insurance companies have undertaken, at renewal, to transmit historic claims details. It is thus possible to associate each claim with an historic flood loss event and so to estimate the global insured cost of each past events that are managed under the Nat Cat system. For the coastal flooding risk evaluation, the historic claims have been consolidated to three events for the studied area: Lothar and Martin (1999), Johanna (2008) and Xynthia (2010).

3.2 Hazard validation

The claims detail provided could be considered as a spatial indicator of the extent of the flood. Initial geographic comparisons between observed and simulated inundated areas and claims were evaluated. These comparisons are shown in Fig. 4 locally for the commune of Châtelaillon-Plage. This example shows firstly that the claims data has not always been effectively localized as examination of the detail shows the claims clustered in the town centre. Indeed, the delineation of inundated areas, often produced a few days after an event, on the basis of satellite data, could shows that claims data input, where not sited in its actual location, could miss some important areas, especially say in the marsh areas. Furthermore, these data inventories could miss sectors where flood water has just runoff and not remained as standing water to be recorded after the initial flood event.

This figure shows also some isolated claims not explained by overflowing simulation alone. This is the case for claims localised into the Vieux-Châtelaillon sector where the elevation of the DTM is relatively important. Often, these problems are explained by the localization of the insurance policy details, but they could also result from local conditions such as streams or urban water network overflowing (as opposed to actual coastal inundation) and cellar inundations.

Two indicators (Wilks, 2011) have been computed to evaluate hazard model performances on the basis of its ability to detect claims:

- the probability of detection (POD): which is the ratio between the claims detected by the model and all of the actual claims. The POD permits evaluation of the capacity of the model to detect claims, the best case being a POD of 100 %;
- the probability of false detection (POFD): which is the ratio between false alarms (policies detected wrongly by the model as being flood affected) and all the policies that have not been the object of claim. The best case is a POFD of 0 %.

Both indicators have been calculated for Xynthia at two scales: the country and the communal scale. At the country scale, the results are a POD of 58 % for a POFD of 4 %, which means that the system missed a significant number of claims (42 %) and selected a non-negligible number of policies that have not been affected. However, the comparison of these policies with areas identified as flood affected allows us to put in perspective our scores as actual inundated areas permitted us only to detect 72 % of claims and also generated false claims reports (POFD = 1.2 %).

The results obtained at the communal scale, presented in Fig. 5, give also complementary information. Firstly, they appear strongly correlated with the results of the hazard model presented previously. Thus, municipalities with high POD and low POFD are generally well simulated in terms of hazard. In the same way, when both POD and POFD are low, the extent of the inundation is generally underestimated. This is the case for the municipalities of La Flotte and Charron that should normally figure in the most affected areas. It appears also that hazard is sometimes overestimated when both POD and POFD are high, notably for the west part of the Isle de Ré or in the sector of Noirmoutier.

The major limit of the hazard model is the quality of topographic data. This is particularly visible in the Fig. 6 that shows a comparison between two DTMs for a same cross section localized in the commune of Yves (south part of the Fig. 3). The two DTMs are the DTM used in this study and a DTM elaborated on the basis of Lidar data (Institut Géographique National, French geographical institute), interpolated with a 25 m resolution with respect to coastal protections levels. The differences between the two DTMs seem very significant with an average value of one metre and up to two metres at the location of the dike. The analysis of the DTM used shows two defaults. The first is that it generally underestimates the elevation of coastal protections and the second is that it seems generally "smoothed" in urban area where it overestimates the elevation of the ground. However, it has the advantage of being more accurate than the ASTER GDEM (Meyer et al., 2011) and to be available all over the French territory, while the RGE® ALTI (©IGN) DTM has just been recently made available for French low-lying areas. Furthermore, the implementation of hydraulic connections such as conduits or bridges needs also to be addressed with a good quality DTM.

The vulnerability model could also explain the scores obtained. The first limit is that the data inventory is not always exhaustive. Indeed, when losses are lower than the amount of the insurance franchise (deductible), claims are generally not declared. This situation could explain the high number of computed false losses. The second limit comes from the localization of the policies. As indicated in Sect. 3.1, this loss localization is deduced from the address transmitted by the cedant. A comparison with the real locus of the policy (and therefore of the loss) has shown that about 30 % of policies are localized in reality at a distance greater than 50 m of the estimated coordinates. The third limit of the vulnerability model is that it often does not distinguish secondary residences from main residences. This could generate a significant number of both false alarms and non-detections. Despite these problems, claims give interesting and original information by localizing areas that have been inundated but perhaps not taken into account in the areas otherwise inventoried.

4 Damage model

4.1 Description

The damage model aims to explain the cost that could be generated according to the magnitude of the phenomena and the vulnerability (policy exposure). Numerous studies have tried to adjust such models on the basis of damage curves permitting to explain the loss (cost or destruction rate) as a function of physical parameters such as water levels, velocity, discharge, etc. (Messner et al., 2007; Scawthorn et al., 2006; Boettle et al., 2011).

In the case of coastal flooding, losses could result from the contact of saltwater with buildings – generating salt and corrosion problems or from the mechanical action of waves or currents in the most exposed areas (André et al., 2013).

$$C_{e,i} = P_{c,i} \cdot T_{d,i} \cdot V_{a,i}. \tag{4}$$

The aggregation of claim amounts permits the computation of the whole event loss, but also the losses per region, per municipality or per insurance company. According to Eq. (4) the claim loss estimation of one insurance policy alone is not consistent: the sum of claim probability will be a good estimation of the real number of claims at the event scale, but will not permit identification of the individual claim loss value.

The two firsts parameters were calibrated on the basis of water levels simulated for the Xynthia event. The claim probability gives the probability of the insured location to be damaged according to its water level during the event. Indeed, the data shows that a large proportion of goods located in an inundated area are not declared as damaged. This absence of claim could come from the eventual protection of the risk (e.g. issues such as local elevation being more important, or the presence of natural or artificial protections, barriers, etc.) or to the low proportion of material damages by comparison to the insurance deductible. The result of the calibration adopting a logistic behaviour, the following equation is used to calculate the claim probability:

$$P_{c,i} = \frac{e^{a+b\cdot \mathrm{WD}_i + c\cdot S}}{1+e^{a+b\cdot \mathrm{WD}_i + c\cdot S}} d, \tag{5}$$

with WD corresponding to the sea water depth and a, b, c, d being four dimensionless parameters. The variable S, qualifying the surge, corresponds to the difference between the maximum water level in sea and the water level corresponding to a two years return period. This variable is calculated for each of the 20 available tide stations and extrapolated along the coastline. This formula permits projection of the number of claims by producing the sum of the probabilities.

The destruction rate is a relationship between the loss amount and the hazard intensity. Indeed, it is often assumed that the more the water levels are significant, the greater the loss will be. In the literature, some studies were shown to express the cost of the destruction rate as a function of the water levels (Prettenthaler et al., 2010; Huttenlau et al., 2010; André et al., 2013). These works often show a very large spread of the losses where there are high water levels. Furthermore, it appears that costs depend also of the nature of the risk type. Thus, in our study, five classes of risk have been selected to calibrate the destruction rates: the individual owner, the individual tenant, the agricultural companies, companies other than agricultural and the other (co-ownership, incomplete, etc.). For each of these classes, the destruction rate has been calibrated according a linear expression, giving the best results in our case:

$$T_{D,i} = a \cdot \mathrm{WD}_i + b. \tag{6}$$

For instance, only water levels are taken into account into the loss probability and the damage function. However, some other variables such as flow duration, flow velocity or the hour at which the phenomenon occur could be tested in the future but this requires a larger sample field of events.

The localization of the policy locus has not always required specific accuracy to calculate the hazard, especially when the localization is at commune or street level precision only. Finally, this model does not permit accurate individual claim statements, but the aggregation of costs at a larger scale permits the production of a representative result.

4.2 Calibration and validation of the damage model

The calibration of the Eqs. (5) and (6) was realized on a small sample of risks for the Xynthia event. The sample chosen was composed of two cedants presenting good quality data and exhaustive claims details for the chosen event. Among these policies, only those geo-localized at the roof top were taken into account. This sample represents 71 778 policies with 736 claims for the coastal municipalities of the French departments affected by Xynthia.

The validation was realized by comparing the total cost for the 12 major cedants affected by the event-representing about 38 % of the market. These total costs are not the sum of claims, but information directly transmitted by the cedants after the event, to overcome the problematic of non-exhaustive claims databases. Like the other studies in the public domain, a high dispersion is observed in the relationship between destruction rate and water height (Prettenthaler et al., 2010; André et al., 2013).

The results of the calibration exercise, presented in the Table 1, show that the validation allows a good estimation of the total cost for the calibration sample, but with a little bias of 3.3 %. This bias, caused by the risk locations that are not localized to the address as well as hydraulic modelling, appears acceptable according to the different uncertainties of the sources. In the same way, the total losses simulated for the validation sample is near the observed total, but with a bias of 2.4 % that seems also acceptable.

4.3 Sensitivity analysis of the damage model

The evaluation of the hazard model discussed previously has shown its limitations, in particular the problems of the DTM quality as well as the limitations of the loss vulnerability database. These limitations are, from our point of view, inherent in the majority of operational systems at such spatial scales. The question is finally to know how the loss estimates that constitute the final modelling product are sensitive to these limitations.

According to de Moel et al. (2012), uncertainties in the damage estimation are as important as uncertainties in the hydraulic boundary conditions. A test was undertaken to evaluate the sensitivity of the damage model to the water levels along the coastline. Thus, the input water levels in of the inundation model have been modified through-out the flood duration (i.e. not only on the maximum water level) on the basis of four scenarios: plus or minus 10 cm and plus or minus 20 cm.

The results of these simulations, presented in the Table 2, show that the uncertainties in coastal water level data are able to generate very different results. Thus, a difference of 10 cm in water level could vary the total loss by 11 to 12 %. In the same way, a difference of 20 cm in level varies the cost by about 21 to 24 %. These important deviations are explained by the increase of the number of risk properties brought into the inundated area. In effect, as illustrated in Fig. 7, a modification of water levels of 10 to 20 cm could significantly change the extent of the inundation and thus, the number of risk properties affected. These differences concern specifically the most flat areas but could have a great influence on the final insurance cost, especially when urban areas are concerned, because of insured property densities.

Upon examining these results, it could be supposed that the influence of the quality of the DTM is in the same order of magnitude as the sea water levels. If the DTM elevation along the coastline presents an error of a few centimeters, all the adjacent area could be affected in terms of water height and loss estimates. The sensitivity to the sea water levels illustrates also the need to take into account the wave setup so as not to underestimate the losses. The fact that the wave setup that could affect the sheltered bays are not taken into account by the model could partially influence the final result. This problem could be overcome by coupling a wave model with the surge model however it could be time expensive and thus, difficult to put in place in operational conditions.

The system developed has been used to estimate four more event losses: the storms Johanna that affected Brittany in 2008, the storm Xaver that occurred at the end of 2013 in the North of France and two events that occurred in the Bay of Biscay at the end of January and at the beginning of March 2014 (Christine). For these last three events, the incurred costs are still not available, but according to the observation, they should be low even if these three events have severely impacted the coastline with damage

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affecting beaches, roads and dikes. The results of the costs estimated for each event and for the market are presented in Fig. 8.

For Johanna, the cost appears to be highly overestimated with an estimation of 74 million against a real cost of about 16 million. This overestimation could be partially explained by the fact that the sector affected has not been used for the calibration. The hazard model seems to overestimate the inundated areas in some densely populated cities generating high costs. Furthermore, in some plane sectors, the DTM elevation induces the inundation of the land even for modest sea water level rises. Finally, it should be noted that the number of available significant events is limited, especially for calibration purposes. The work to date relies mainly on the Xynthia event which concerns the majority of the available claims information. These two points explain also the high costs generated for the Xaver and Christine events. The case of the 30 January 2014 event seems to be more consistent. In the sector affected, the inundated areas extent seems consistent and serves to lower costs in accordance with the observations. Finally, even if the model seems to overestimate the cost of moderate events, the estimations constitute nevertheless a useful indicator of the magnitude and the extension of an event.

5 Conclusions

The system presented in this article permits the estimation of insurance related losses due to coastal flooding events in France, especially on the Atlantic coast. The modelling chain, even if limited and still in an early stage of development, is, when applied on a large scale effective in satisfactorily estimating the magnitude of the resultant financial losses two to three days after the event occurrence. The estimations are consistent with the few historical events available (especially for Xynthia storm in 2010), and for calibration and validation of the approach.

The coastal flooding modelling at a large scale and within an operational perspective constitutes a difficult exercise that needs to match the scale of the output results and the accuracy and the complexity of the represented processes. The results emphasise the importance of the quality of topographic information, which constitutes one of the main limiting factors of the system. In order to improve this aspect, the use of other topographic data such as LiDAR (RGE® ALTI) will be investigated in the future. The results obtained by the sensitivity tests underline also the need for a good estimation of sea water levels and of the wave setup process, although a future addition of a wave model should improve the system. The validation of the model is also limited by the lack of data due to the limited number of events in France, since the origin of the national Nat Cat scheme.

Finally, this study illustrates the usefulness of hydrodynamic models for an operational modelling of storm surge. In this situation, the insurance claims data constitutes a good indicator of the extent of the inundated areas which could help in the validation of sea surge models. The deterministic model, presented in this article, constitutes the basis of the probabilistic approach under development at CCR. This probabilistic model will be used to evaluate the exposure of the French coast to coastal flooding risk. It is based on the combination of fictive events and hazard scenarios generated by the inundation model. This probabilistic model should allow estimation of the financial exposure of CCR, as reinsurer, the French state and of insurance companies to storm surge events and losses in the future, but also the potential consequences of sea level rises within climate change scenarios.

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Table 1. Observed and simulated losses at country scale.

	Simulated (Million euros)	Observed (Million euros)	Bias
Calibration sample	54.0	54.7	0.011
Validation sample	213.7	206.5	0.033
Total	267.7	261.2	0.024

Table 2. Losses computed for the market at country scale on the basis of several inundation scenarios.

	Difference between the scenario and the initial water levels (cm)				
	−20	−10	0	+10	+20
Losses (Million euros)	594	671	755.3	844	934
Bias	0.21	0.11	0	0.12	0.24

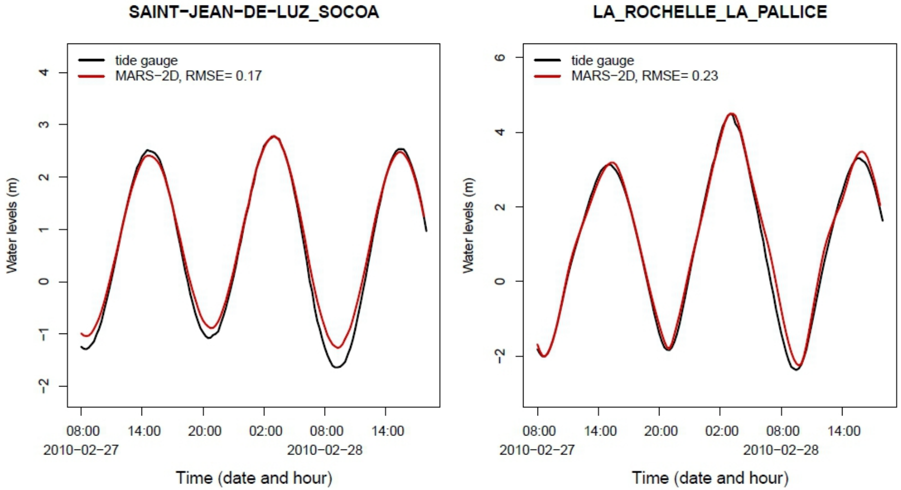

Figure 1. Comparison between the observed tides and the water levels estimated by PREVIMER for the Xynthia event at two gauge stations.

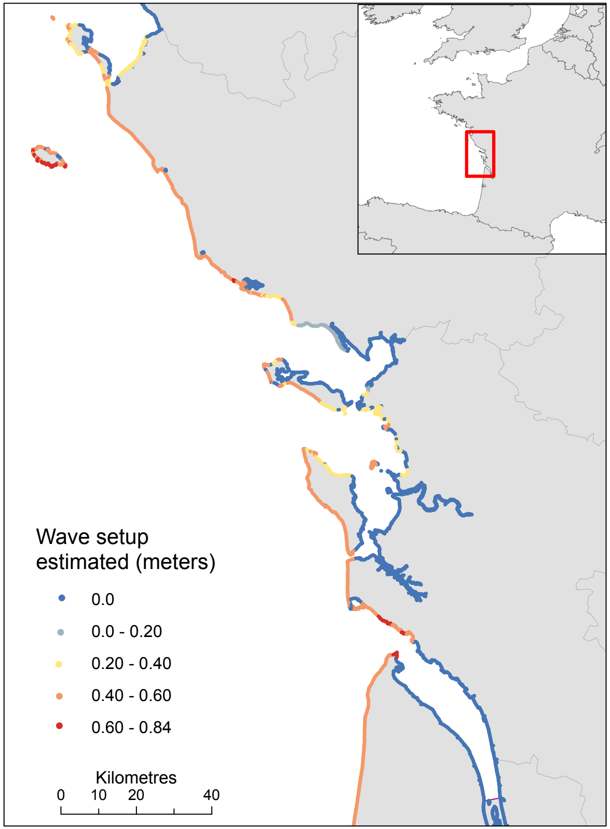

Figure 2. Maximal estimated local wave setup, computed according to Stockdon et al. (2006) along the coastline for the Xynthia event.

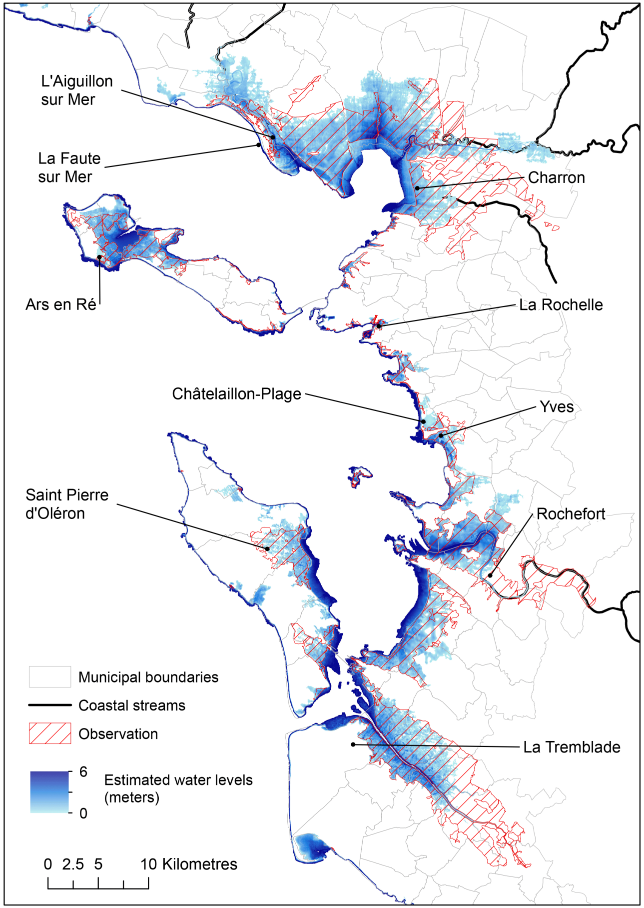

Figure 3. Simulated and observed inundated areas for the coastal municipalities of Charente-Maritime for Xynthia event.

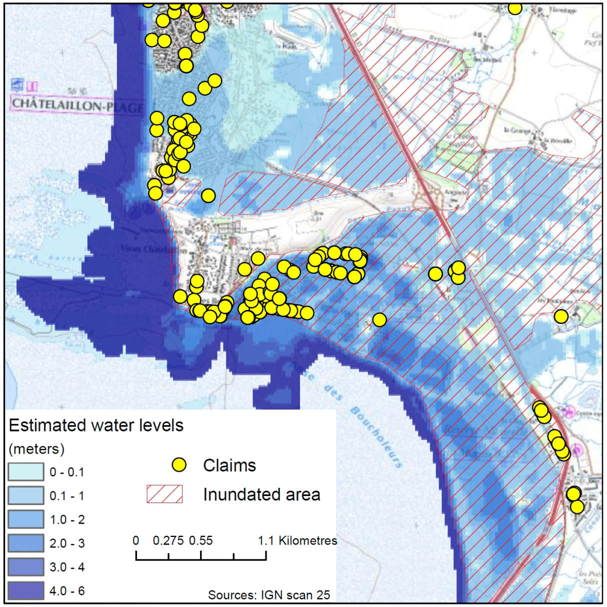

Figure 4. Claims and inundated areas for the Chatelaillon-Plage municipality during the Xynthia event.

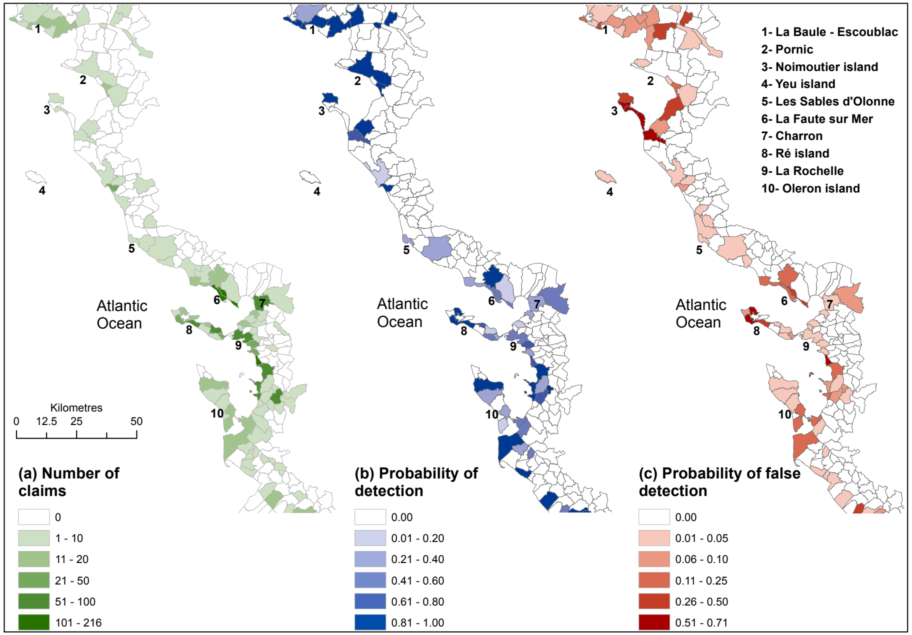

Figure 5. Performances of the system, obtained by comparing claims and insurance policies to the water levels simulated.

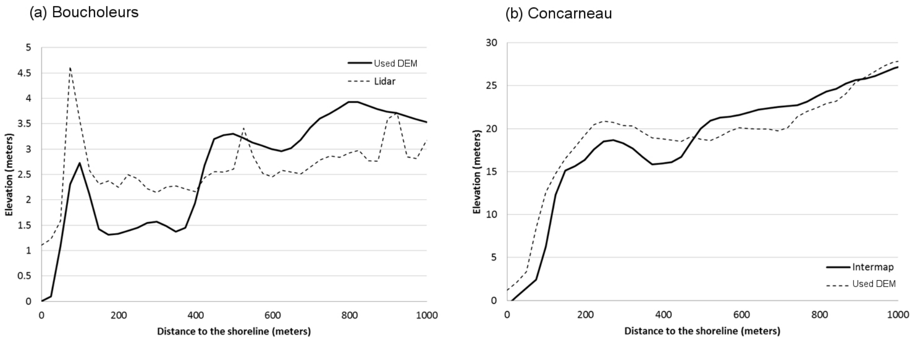

Figure 6. Comparison beetween the DTM used in this study and a DTM elaborated from Lidar observations, interpolated at a 25 m resolution, for a cross section located in the Boucholeurs area **(a)** and near the Concarneau city **(b)**.

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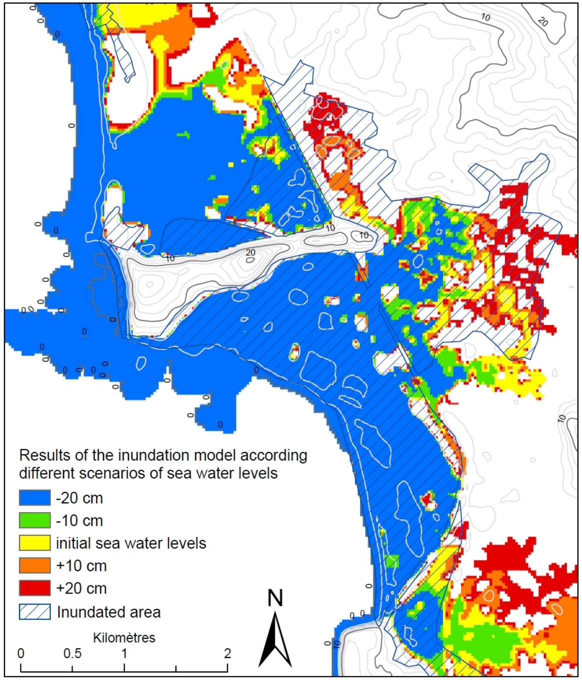

Figure 7. Results of the sensitivity test of the inundation model to the water levels estimated in sea.

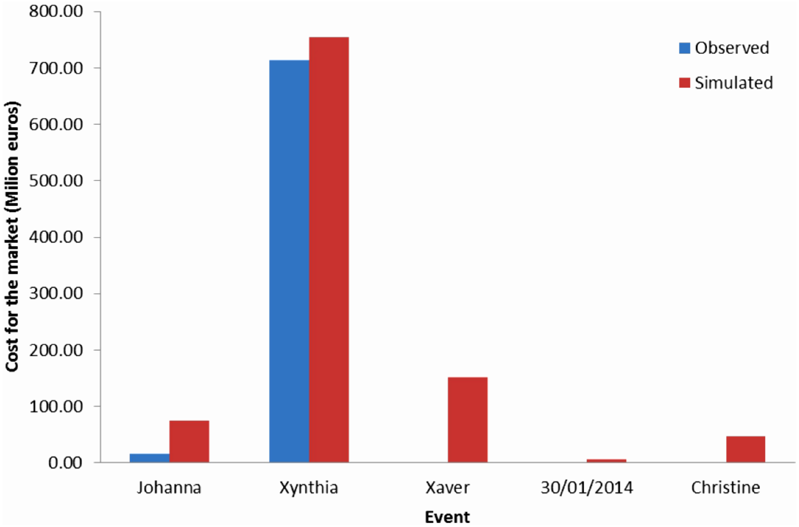

Figure 8. Comparison beetween the losses observed and simulated at country scale on five recent events.The losses of the Xaver event and the two 2014 events are not yet available.