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# Assessing changes on urban flood vulnerability through mapping land use from historical information

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## Abstract

This paper presents a diachronic appraisal of flood vulnerability of two French cities, respectively Besançon and Moissac, which have been largely impacted by two ancient floods in January 1910 and March 1930. Both flood events figured among the most significant events recorded in France during the XXth century. An analysis of historical sources allows the mapping of land use and occupation within the flood extent of the two historical floods, both in past and present contexts. It gives an insight of the complexity of flood risk evolution, at a local scale.

## 1 Introduction

Directive 2007/60/EC on the assessment and management of flood risks draws a new framework for the promotion of historical information. It aims to reduce and to manage the risks that floods pose to human health, environment, cultural heritage and economic activity. The Directive requires Member States to first carry out a preliminary assessment by 2011 to identify the river basins and then associated coastal areas at risk of flooding. For such zones the following steps consist in drawing up flood risk maps by 2013 and establishing flood risk management plans focused on prevention, protection and preparedness by 2015. The Directive applies to inland waters as well as all coastal waters across the whole territory of the EU. In France, a national Historical Database on floods (http://bdhi.fr/) has been opened to the public in 2015, based on the inventory of major floods in France produced in 2011 within the framework of the EU Flood Directive (Lang and Coeur, 2014; Lang et al., 2012). It contains a description of 176 "remarkable" flood events described from 1770 to 2011.

A key issue of the Flood Directive is to accurately assess the flood risk. A commonly accepted definition of flood risk is the combination between a flood hazard and the vulnerability of assets exposed (Cardona et al., 2012). In suit with this definition, the French Government distinguished two main steps for flood risk assessment. A first





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step consisted in mapping the potential flood extent in order to evaluate the number of assets exposed. Starting from this data a second step consisted in censing the asset exposure and vulnerability. For this purpose some indicators had been adopted, according to potential impacts on human health, economic activity, environment and cultural heritage within the potential flood extent. To name a few, they are for instance the number of population living, the number of one storey buildings, the number of employments, the number of nuclear power stations, the area of remarkable built heritage, etc. Following this approach, the flood risk assessment drew up a contrasted overview of actual flood risk. The results indicate a strong and unequal assets exposure over the French territory, and raise some concerns in a context of increasing flood damages (SwissRe, 2015) and global change.

In order to consider a potential increase of flood risk, the assessment has however to be considered at a large temporal scale. The indicators developed during the preliminary phase are in fact closely correlated to the actual situation and raise some questions about the past situation of vulnerability. How do we assess the vulnerability and exposure situations during past flood events with uncertain and sparse historical sources? Can we confirm an increase of stakeholder's exposure and vulnerability based on a diachronic analysis of past disasters? Are these disasters still relevant and easily integrated into risk management policies as indicated in the Flood Directive text?

Assessing flood impacts and understanding the past vulnerability of a territory is an essential step towards a long term mitigation strategy (Changnon et al., 2000). Firstly, it allows a better understanding of the circumstances that leaded to a disaster. And secondly, it helps to shed the light on the actual state of the vulnerability in a territory. This vulnerability (especially visible through the exposure of the assets) has to be seen as the result of a complex historical evolution, partly related to the occurrence of past damaging flood events (Barrera et al., 2006).

To carry out these issues this paper proposes to highlight the interest of historical information through a transdisciplinary and mapping approach (Danière, 2014). The study is based on the set of 176 major French floods which offers an opportunity to





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explore the past flood events vulnerability. We applied the methodology on two case studies selected for their "remarkability": the January 1910 flood event (generalized to all the North-East of France) and the March 1930 flood event (focused on the Tarn River). We focused the analysis on two cities, Besançon and Moissac, each one largely affected by one of these two events. After a brief presentation of the two flood events (Sect. 2), we present the methodological framework used for mapping the vulnerability (Sect. 3). It has been applied on the two case studies (Sect. 4), illustrating the past and present vulnerability situations in the two cities. Finally, some keys are given (Sect. 5) about the interest of historical information for assessing vulnerability changes during the XXth century.

## 2 Case studies

### 2.1 Selection of two remarkable flood events

Based on the 2011 inventory of 176 major floods in France, Boudou (2015) selected the most remarkable events since 1770. Using a transdisciplinary methodology, an evaluation grid based on three main features was established: (1) flood intensity according to several criteria (return period of the maximum peak discharge; duration of submersion; dike breaches or log jams); (2) flood severity with two main indicators, flood damages (number of fatalities, economic loss) and social, media or political impacts of the event (establishing a new risk policy, calling for international solidarity to face the crisis...); (3) spatial extension of damages. A second level of selection leaded to focus on 9 events showed in Fig. 1 (January 1910, March 1930, October 1940, December 1947/January 48, December 1959, January 1980, November 1999, December 2000/April 2001). These flood events cover all flood typologies (oceanic/snowmelt/Mediterranean floods, marine submersion, cyclones, dam breaking) and are considered as some of the most remarkable in accordance with the evaluation grid.





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In this paper we will investigate the two oldest selected events, respectively in January 1910 and March 1930, focusing on the urban situation in Besançon and Moissac (Fig. 2). The aim is to focus on two cities which have been significantly flooded in the past and to understand how their vulnerability to flood has changed until now.

## 2.2 The January 1910 flood event in Besançon (Doubs River catchment)

Among the 9 floods selected as remarkable according to the evaluation grid, the flood of January 1910 reaches one of the highest score (Fig. 1). This flood event is mostly known for being the most significant flood that affected the city of Paris, with a return period of about one hundred years. There were a relatively small number of fatalities (4 direct + 11 indirect deaths), but the impact within the Paris region was extremely high, with 150 000 affected people and about 1.5 billion of euros of damages. Despite the fact that a large part of the Northern French territory was also affected, the attention of society and the memory have been focused on Paris. In order to demonstrate the remarkability of this event, not only for the Seine catchment area but also for more rural regions, we then decided to focus our study on the Doubs basin where the flood of January 1910 remains one of the most significant historical floods and the highest water level recorded in the city of Besançon. The flood event was triggered by a heavy rainfall event from the 17 to 21 January, plus the presence of a large snow cover after a wet winter which leaded to a significant snow melting. A large part of the old city of Besançon was flooded, with huge damages. Many shops, houses and their basements were inundated, causing important losses of furniture. The streets of the town also particularly suffered due to the high flow velocity. In total, the cost of the flood at Besançon is estimated around 2.5 million of euros.

According to several documentary sources (Allard, 1910), it appears that the hydrometeorological conditions of the event (return period less than 100 years) cannot explain why the flood level was so high through the old city. Such exceptional water level in the city centre is the consequence of energy losses along the bridges of the town. These energy losses were larger than usual (cf. Fig. 3 in comparison with the 1882 and





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1896 flood events) due to the accumulation of pieces of wood (about 35 000 $m^3$), resulting from the submersion of a paper factory a few kilometres upstream to Besançon, contributing significantly to the raise of the water level.

A work with archive sources also revealed some major failures of the flood warning during the event. Surprised both by the flood arrival and its intensity, the local authorities did not succeed to establish temporary protecting structures at the different opened gates ("postern gates") and directly contributed to the submersion of the city (Fig. 4).

### 2.3 The March 1930 flood in Moissac (Tarn River catchment)

At the end of February 1930, a large Mediterranean rainfall event occurred in the South-West of France. Due to its intensity and its unusual occurrence date (at the end of a wet winter) the rainfall event triggered to an exceptional flood event (Pardé, 1930). The following flood hazard intensity can be judged exceptional for the downstream part of the Tarn catchment, with a return period significantly larger than 100 years. Approximately 210 fatalities were recorded during the flood event, leading to one of the most damaging flood event ever recorded in France and surely the most significant for the XXth century. The economic loss for the all-region around is estimating around 600 million of euros.

One of the striking issues of the disaster can be found in the concentration of the damages in the city of Moissac (120 deaths for a total of 210). Reconstructing and mapping the flood chronology using historical sources enhances a better understanding of the circumstances of the disaster (Fig. 5). The 3 March 1930, the flood arrived in the town. Before 18:30 the Tarn River was already overflowing the main channel, both on left and right sides. Fortunately the city centre was protected by three main dikes and the embankment of the railway line. From 18:30 to 23:00, the water level raised and the flood extent covered the area between the main dikes at the eastern part of the city. Around 23:00, at the maximum discharge value (estimated around 8000 $m^3\,s^{-1}$), three breaches suddenly appeared along the embankment railway. These breaches leaded to a sudden outburst of the dikes and to the final submersion of the city.

According to the death locations and the disaster feedbacks, the dike failures can be considered as one of the key issues of the disaster. The flood abruptness and fierceness induced a surprise effect for the inhabitants of Moissac and the collapses of more than 600 hundreds houses. The typical kind of housing of this region, made with raw bricks especially vulnerable to water crushing forces, also has to be noticed as a major factor in the damaging process of the city.

## 3 Methodology for monitoring changes in flood vulnerability

### 3.1 Relevance of historical events in the present context?

One of the main requirements of the Flood Directive is to identify areas with a potential high level of flood risk, based on historical floods that would have significant adverse consequences if they occurred again. As the consequences are both depending on the flood hazard and the personal, social and economic assets located in the flood risk zones, one of the main concerns is to assess the evolution over time of local vulnerability of city centres. For both case studies, the main casualties and/or economic losses within the catchment were located in one city. But some aggravating factors were time dependants, such as woody debris upstream bridges at Besançon or dike failures at the east of Moissac. Other aggravating factors were related to social vulnerability, such as failures on flood warning at Besançon or vulnerable building materials at Moissac.

In order to better understand the local disaster process, we will monitor changes in flood vulnerability, comparing the past and the present situations. Several questions have to be addressed. Is it possible to correctly depict the vulnerability over time according to the available sources? Does a mapping of land use provide enough information to identify indicators of vulnerability? Can we establish some scenarios about the impact of a future flood based on a historical flood?





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After a preliminary analysis by geo-referencing historical information in the present context, we will consider the mapping of land use and the counting of the population at risk, from past to present.

### 3.2 A dynamic mapping to locate historical information

A preliminary step of this work consisted in the implementation of a dynamic mapping with a spatial display of the historical information formerly collected. The historical corpus made up of various document formats and sources was included in a GIS by locating the information available. Some place names have however changed since the flood event date which required supplementary efforts.

Such dynamic consultation of historical information is not only for interest to correctly locate the various sources of information on flood vulnerability. It can also be used to develop risk awareness and risk culture on an exposed territory. As an example, the high-water mark inventory developed in the Seine river catchment (www.reperesdecrues-seine.fr/carte.php) provides a dynamic mapping which is easily understandable and interactive for general public contrary to the maps resulting from hydraulic or hydromorphogenic modelling (de Moel et al., 2009).

### 3.3 Evolution of land use

We will address the structural exposure and the structural vulnerability (Fig. 6) using simplified descriptors which remain consistent with the level of data availability and accuracy of historical information (Barnikel and Becht, 2003; Barnikel, 2004).

Firstly the study of structural exposure associated with urban growth analysis provides information for built-up area evolution. Secondly structural vulnerability analysis based on land-use classification provides relevant information to evaluate the nature of structural exposure evolution. Use of historical information at least describing the land cover on different dates is required. For example, historical maps and aerial photos often depict the built-up territory for a specific year.





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In order to perform a spatial analysis of historical maps, their integration into a GIS was required. Three steps were executed: scanning, georeferencing and digitalizing supported by a referenced geometry (Fig. 6a) (Rumsey and Willimas, 2002; Levin et al., 2010). A set of historical maps and aerial photographs produced by the French National Institute of Geographic and Forest Information (IGN) was used to depict the urban extension at block of house scale. These raster data were imported and georeferenced. A spatial database (BD TOPO) coming from IGN, describing the present French territory and its infrastructures was used to select control points and to evaluate distortions during the digitizing step. During this last step, information from topographic maps was vectorized into a unique "historical layer". In this way, each object gets a spatial reality (via the GIS representation) and a temporal reality (by associating a temporal field to indicate its existence for a specific year). Consequently, the "historical layer" makes it possible to depict some "temporal snapshots" (Langran and Chrisman, 1988; Gregory and Healey, 2007) of the urban fabric: space is discretized based on available information at the event period.

Subsequently, the description of "historical layer" objects provides information on the kind of structural exposure. A land-use classification was achieved based on a nomenclature adapted from an Urban Atlas of European Environment Agency, according to historical information constraints (Fig. 6b). A first geomatic processing was run to discretize the residential buildings on a 0.25 ha grid. In each mesh, a density criterion was applied, based on the part of buildings footprint, leading to a partition between dense and sparse areas. In order to enhance the classification, a second processing was then run, using a proximity criterion for each building, by the number of buildings within a 200 m radius (continuous and discontinuous buildings). Local information related to the location and the natures of non-residential constructions were added. BD TOPO data were used to describe current time and a punctual layer was built with our "historical corpus" information for ancient time.

### 3.4 Census of the exposed population within the flood extent

Human exposure is accounted for, by census or an estimation of resident population. The aim was to disperse a raw demographic data throughout the blocks of houses by following its evolution at different scales (Wu et al., 2008). Maps produced could shed the light on the evolution of human exposure within the flood extent.

To assess the current living population within the flood extent, we applied a formula to redistribute at block of house scale two French National Institute for Statistics and Economic Studies (INSEE) demographic data sets. The first one is defined at infra-municipal scale with IRIS data use (Infra-urban statistical area). The second one is based on tax household estimation in a 200 m × 200 m grid. These datasets were distributed through residential blocks of houses, based on a volumetric method (Lwin and Murayama, 2009) in proportion of building footprint times the vertical density, according to the building height:

$$\text{Developped area} = \frac{\text{building height} \times \text{buiding floor area}}{\text{average storey height}} \quad (1)$$

Historical information, as an old census or a raw demographic data, was required to census or to estimate (Ekamper, 2010) the exposed population at the time of disaster. General census reports are available for every French municipality (sometimes online), generally every 5 years until 1946, with some exception. These documents contain municipal population in nominative list, gathered by building and street, on different dates. The comparison between past and present exposed population within the flood extent should take account the possible evolutions of census methodology over time.

## 4 Change of vulnerability based on two case studies

We will now consider the change of vulnerability on the two case studies, from past to present, using historical sources and current information.





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## 4.1 Besançon vulnerability to the January 1910 flood

Figure 7 displays the land use within the 1910 flood extent in Besançon, based on 1910 and 2013 contexts. No significant change can be seen on structural vulnerability, according to the spatial extent on the urbanized area. As Besançon downtown is located within a meander of the Doubs River, with no opportunity of spatial expansion or urban densification, there was no increase of structural exposure, apart for the hospital area. Despite the city experienced a spatial expansion in North, on the right bank, it is located outside our zoning at a larger scale.

According to the land use classification, we can notice significant changes within the various activities. There was a fall in military function, in favour of an increase of the administrative and public function. While the military areas decreased of 74 % between 1910 and 2013, the administrative areas were multiplied by 12. A reduction of human exposure is noticeable between 1911 (the census year closest to the 1910 flood) and 2013 with a 24 % decrease of the downtown population.

The demographic evolution is represented on Fig. 8 at block of house scale, reflecting the household decrease (reduction of inhabitants per building) and some removal of residential function (reduction of inhabited building within the downtown).

## 4.2 Current Moissac vulnerability to the March 1930 flood

The Moissac cartography gives an opposite diagnostic, with an important increase of structural vulnerability within 1930 flood extent (Fig. 9). Build-up surface areas spread by 122 % between 1930 and 2013. Such spatial extension is explained by new residential (mainly housing estate) and economic buildings on the East downtown and by a progressive densification on the low density area on the left flood plain.

Despite a new distribution of the population (Table 1), the human exposure did not change significantly. The reduction of the downtown population density is compensated by a spatial expansion (Fig. 10). The human exposure mainly increased on the downtown eastside, especially in the area located between the two levees. It should





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be noted that no general census report was available for Moissac in the 1930s. The 1930 exposed population was therefore estimated through a rough demographic data set, provided from an internet database holding historical population census at a municipality scale (http://cassini.ehess.fr), and then dispersed based on the volumetric method.

### 4.3 A diachronic appraisal of flood risk evolution

These two case studies shed the light on the complexity of flood risk evolution. At a large scale of a country, it is clearly admitted that the increase of flood damages during the last decades is induced by a general increasing of flood vulnerability (Kron, 2002; Kundzewicz et al., 2014; Smith et al., 2014). At a local scale, where topographic, social and economic context are crucial, it is necessary to have an in-depth analysis.

In Besançon, flood risk vulnerability decreased since 1910, but with significant land-use changes. Submersion frequency changed in the historical centre, due to safety measure establishment, especially with the construction of mitigation structures such as cofferdams to close the postern-gates. Some uncertainties remain to represent the flooded area in case of a 1910 flood, as opposite effects come into play. The log jams at the bridges are not expected to be repeated, but additional hydraulic losses have been introduced by new hydraulic structures since 1910. Nowadays the reference flood selected in the regulatory documents is a simulated flood larger than the January 1910 flood.

In Moissac, the trajectory of the vulnerability follows a more contrasted evolution. As in various French regions, the city experienced a growth spatial extension since 1930, characterized by an important housing estate development. One critical point is the development of one-storey buildings, leading to a higher human and structural vulnerability due to the lack of refuge floor. At the opposite, building quality improved. During the 1930 flood the house collapses in Moissac and the correlated fatalities were closely related to the material used for its construction. In order to decrease weakness in the structures, new materials and architecture technics were then used during the





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reconstruction step. Another positive evolution is related to the improvement of safety measures, especially due to progress in flood warning and population evacuation by the civil protection services. Today, the 1930 flood in Moissac, which return period is estimated around 250 years, is considered as the reference hazard in the local regulatory document of flood risk. This territory would remain vulnerable, especially to dike failure risks.

## 5 Conclusion and perspectives

This paper presented a case study on the urban vulnerability of two French cities which have been largely impacted by two ancient floods in January 1910 and March 1930. It gives an insight of the complexity of flood risk evolution, with local characteristics. Mapping historical sources can provide reliable information on the past flood vulnerability, given some preliminary work. A first step is necessary to correctly locate and geo-reference historical information within the present geographic reference system. Qualitative information (pictures, historical accounts . . . ) can be interpreted to complement some historical maps on land use. The assessment of population at risk within spatial units can be deducted from technical documents with nominative lists of persons as well from ancient censuses. Historical information on past floods can therefore be useful when building scenarios on the future possible floods. It is also important to keep in mind the associated uncertainties on historical data and to use relevant scales when mapping vulnerability indicators.

As usual, a diachronic appraisal of flood risk evolution at a local scale implies a good knowledge of the general context of the socio-economic development of territories, as well as evolutions of risk memory and perception. According to the data availability, this paper focused on a small part of vulnerability. In order to complete a total flood vulnerability analysis, some other indicators should however be taken into account. After Xynthia storm surges in 2010 (41 fatalities due to floods in France), Vinet et al. (2012)





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showed for instance that the age of the population age is a key component of local vulnerability.

This paper focused on flood vulnerability that is an important part of the flood risk. Parallel work is however also necessary on flood hazard, in order to simulate past floods in a present context, taking into account modifications of the river and flood topography and hydraulic works (dikes, weir, dams ...).

*Author contributions.* M. Boudou established the evaluation grid used for the selection of "remarkable" flood events. He collected data on the two historical floods and produced thematic maps on flood hazard. B. Daniere did a dynamic mapping to locate historical information and thematic maps on flood vulnerability. M. Lang did the supervision of the writing of the paper.

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## References

Allard, M.: Les récentes inondations à Besançon, Bibliothèque et archives municipales de la ville de Besançon, 1910.

Barnikel, F.: The value of historical documents for hazard zone mapping, Nat. Hazards Earth Syst. Sci., 4, 599–613, doi:10.5194/nhess-4-599-2004, 2004.

Barnikel, F. and Becht, M.: A historical analysis of hazardous events in the Alps – the case of Hindelang (Bavaria, Germany), Nat. Hazards Earth Syst. Sci., 3, 625–635, doi:10.5194/nhess-3-625-2003, 2003.

Barrera, A., Llasat, M. C., and Barriendos, M.: Estimation of extreme flash flood evolution in Barcelona County from 1351 to 2005, Nat. Hazards Earth Syst. Sci., 6, 505–518, doi:10.5194/nhess-6-505-2006, 2006.

Boudou, M.: Caractérisation de neufs évènements majeurs d'inondations en France au XXème siècle: contribution à la valorisation de l'information historique pour la gestion prospective des risques, PhD, Univ. Montpellier 3, in preparation, 2015.

Cardona, O. D., Van Alast, M. K., Birkmann, M., Fordham, M., McGregor, G., Perez, R., Pulwarty, R. S., Schipper, E. L. F., and Sinh, B. T.: Determinants of risk: exposure and vulnerability, in: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation, edited by: Field, C. B., Barros, V., Stocker, T. F., Qin, D., Dokken, D. J., Ebi, K. L., Mastrandrea, M. D., Mach, K. J., Plattner, G.-K., Allen, S. K., Tignor, M., and Midgley, P. M., a Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press, Cambridge, UK, and New York, NY, USA, 65–108, 2012.

Changnon, S. A., Pielke, R. A., Changnon, D., Sylves, R. T., and Pulwarty, R.: Human factors explain the increased losses from weather and climate extremes, B. Am. Meteorol. Soc., 81, 437–442, 2000.

Danière, B.: Analyse cartographique de l'évolution de la vulnérabilité en zone urbaine face aux inondations dites remarquables, Master 2 Univ., J. Monet Saint-Etienne, Irstea Lyon, 111 pp., 2014.

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.

Ekamper, P.: Using cadastral maps in historical demographic research: some examples from the Netherlands, The History of the Family, 15, 1–12, 2010.

Gregory, I. N. and Healey, R. G.: Historical GIS: structuring, mapping and analysing geographies of the past, Prog. Hum. Geog., 31, 638–653, 2007.

Kron, W.: Keynote lecture: Flood risk = hazard × exposure × vulnerability, in: Proceedings of the Flood Defence, Science Press, New York Ltd., ISBN 7-03-008310-5, 82–97, 2002.

Kundzewicz, Z. W., Kanae, S., Seneviratne, S. I., Handmer, J., Nicholls, N., Peduzzi, P., Mechler, R., Bouwer, L. M., Arnell, N., Mach, K., Muir-Wood, R., Brakenridge, G. R., Kron, W., Benito, G., Honda, Y., Takahashi, K., and Sherstyukov, B.: Flood risk and climate change: global and regional perspectives, Hydrolog. Sci. J., 59, 1–28, 2014.

Lang, M. and Coeur, D.: Les inondations remarquables en France, Inventaire 2011 pour la directive Inondation, Ed. Quae, Paris, 640 p., 2014.

Lang, M., Coeur, C., Bacq, B., Bard, A., Becker, T., Bignon, E., Blanchard, R., Bruckmann, L., Delserieys, M., Edelblutte, C., and Merle, C.: Preliminary Flood Risk Assessment for the European Directive: inventory of French past floods, in: "Comprehensive Flood Risk Management", Kjlin and Schweckendiek Ed., Taylor and Francis Group, London, ISBN 978-0-415-62144-1, 1211–1217, 2012.





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Langran, G. and Chrisman, N. R.: A framework for temporal geographic information, Cartographica, The International Journal for Geographic Information and Geovisualization 25, 1–14, 1988.
Levin, N., Kark, R., and Galilee, E.: Maps and the settlement of southern Palestine, 1799–1948: an historical/GIS analysis, J. Hist. Geogr., 36, 1–18, 2010.
Lwin, K. and Murayama, Y.: A GIS Approach to Estimation of Building Population for Micro spatial Analysis, Transactions in GIS, 13, 401–414, 2009.
Pardé, M.: La crue de mars 1930 dans le sud et le sud-ouest de la France: Genèse de la catastrophe, Revue Géographique des Pyrénées et du sud-ouest, 1, 3–99, 1930.
Rumsey, D. and Williams, M.: Historical maps in GIS, edited by: Knowles, A. K., past place: GIS for history, ESRI Press, Redlands, CA, 1–18, 2002.
Smith, A., Martin, D., and Cockings, S.: Spatio-temporal population modelling for enhanced assessment of urban exposure to flood risk, Appl. Spatial Anal. Pol., 1–19, doi:10.1007/s12061-014-9110-6, 2014.
SwissRe: Natural catastrophes and man-made disaster in 2014: convective and winter storms generate most losses, Sigma, 2, 50 pp., 2015.
Vinet, F., Lumbroso, D., Defossez, S., and Boissier, L.: A comparative analysis of the loss of life during two recent floods in France: the sea surge caused by the storm Xynthia and the flash flood in Var, Nat. Hazards, 61, 1179–1201, 2012.
Wu, S. S., Wang, L., and Qiu, X.: Incorporating GIS building data and census housing statistics for sub-block-level population estimation, Prof. Geogr., 60, 121–135, 2008.





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**Table 1.** Exposed population in 1930 and 2013 for each submersion zone (cf. Fig. 10) in Moissac.

| Flooded area (Fig. 10) | 1930 | 2013 |
|---|---|---|
| (1) | 4089 | 1160 |
| (2) | 1044 | 2880 |
| (3) | 2267 | 2000 |
| Total | 7400 | 6040 |





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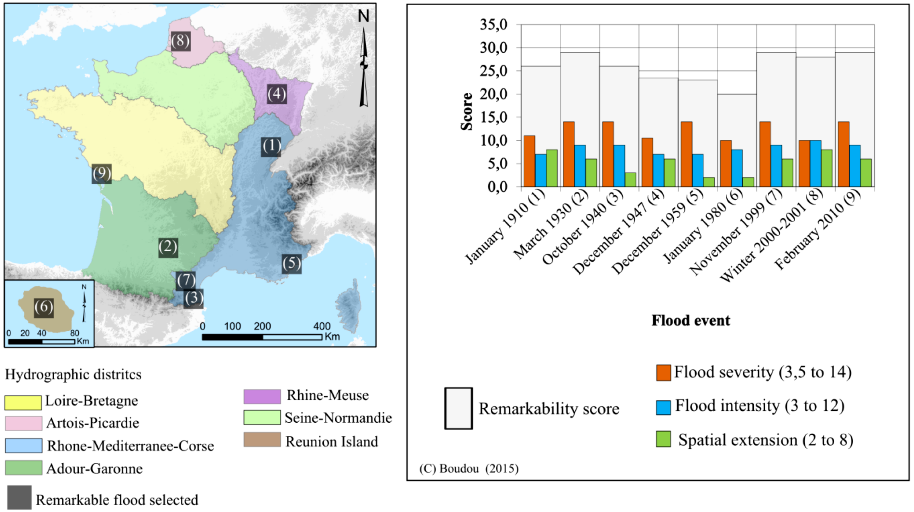


**Figure 1.** Location map of the 9 most remarkable flooding events selected and table of the remarkability score related (Boudou, 2015).





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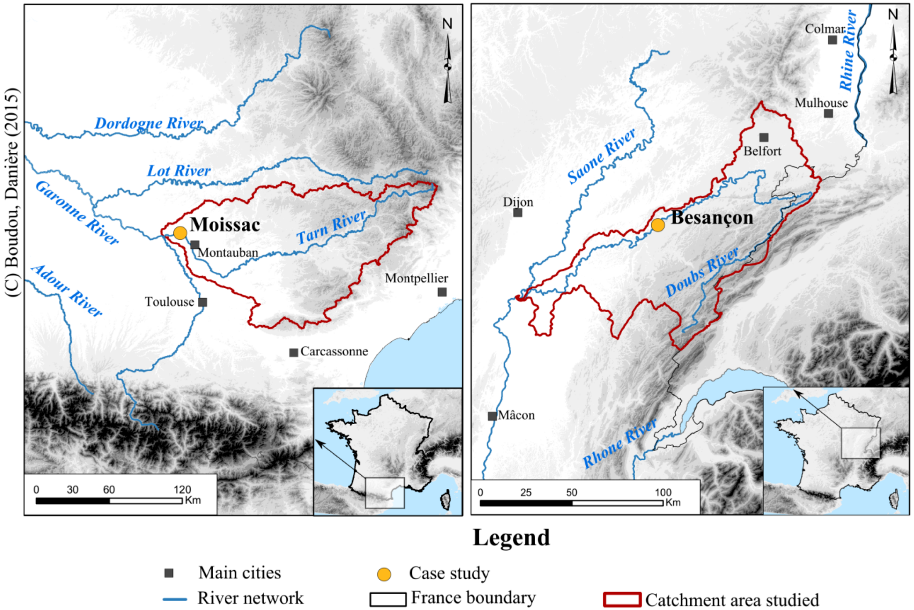


**Figure 2.** Location of the case studies: (left) Tarn basin and Moissac city; (right) Doubs basin and Besançon city.





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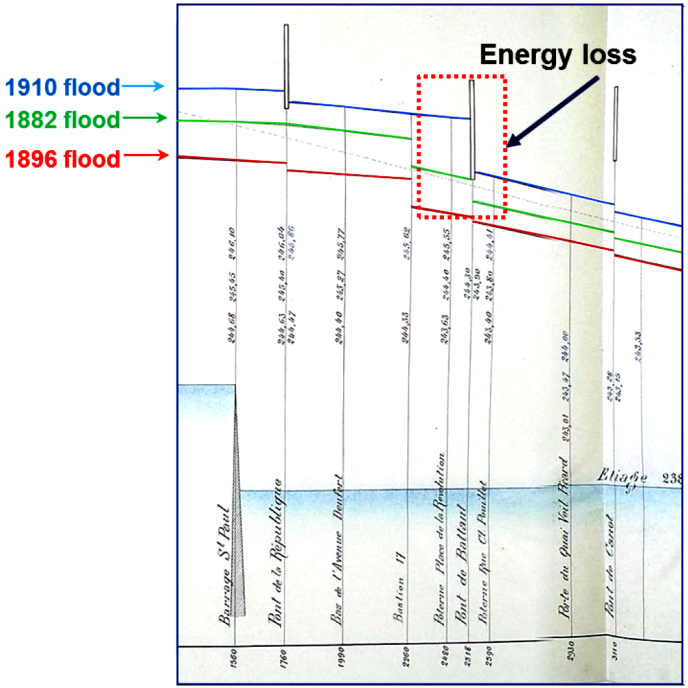


**Figure 3.** Longitudinal profile of the Doubs River and flood inter-comparison (sources: Doubs Departmental Archives, modified by Boudou, 2015).





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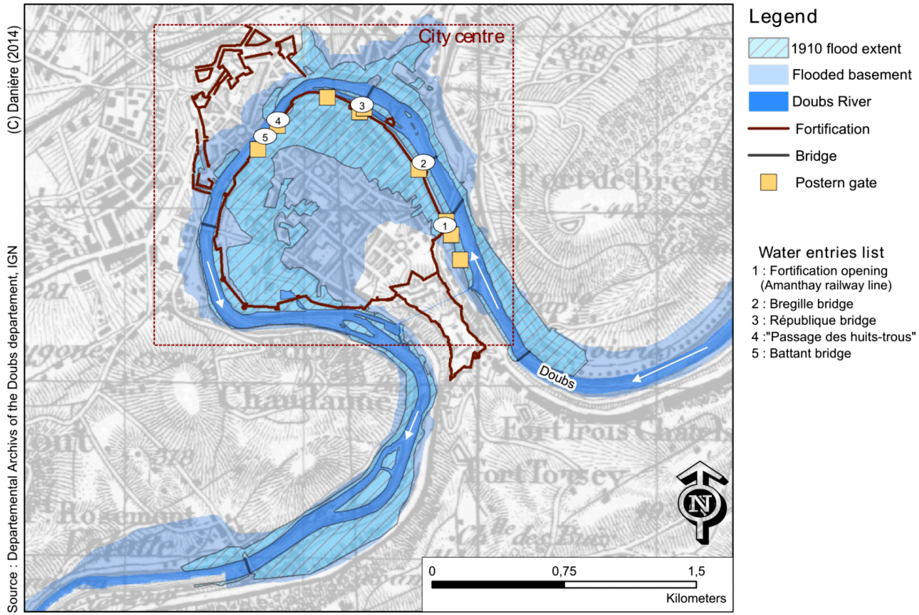


**Figure 4.** Old Besançon city centre with characteristic water entries during the 1910 flood event.





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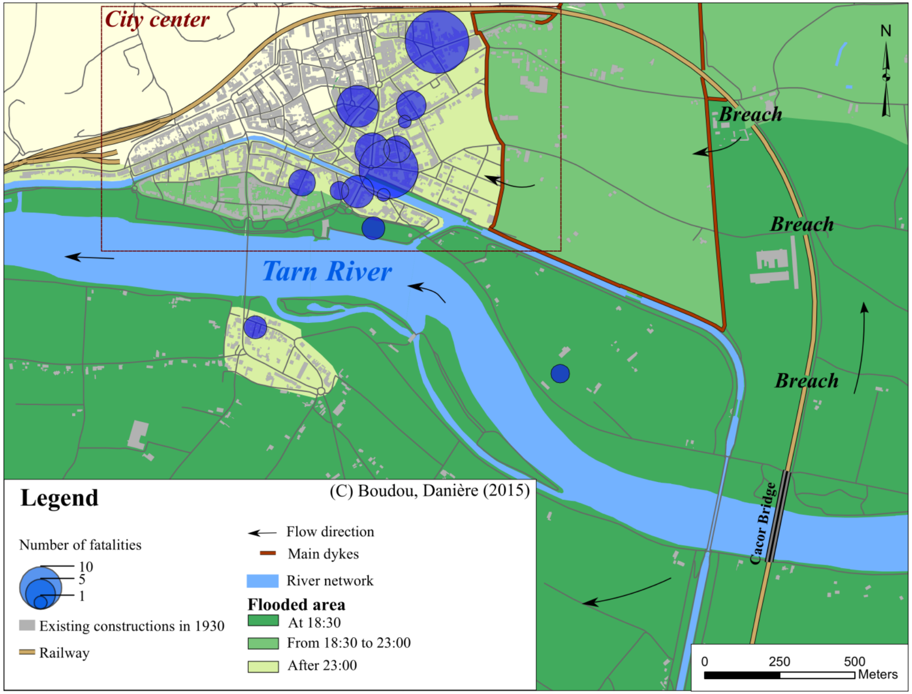


**Figure 5.** Flood chronology and location of fatalities during the 3 March 1930 flood event in the city of Moissac.

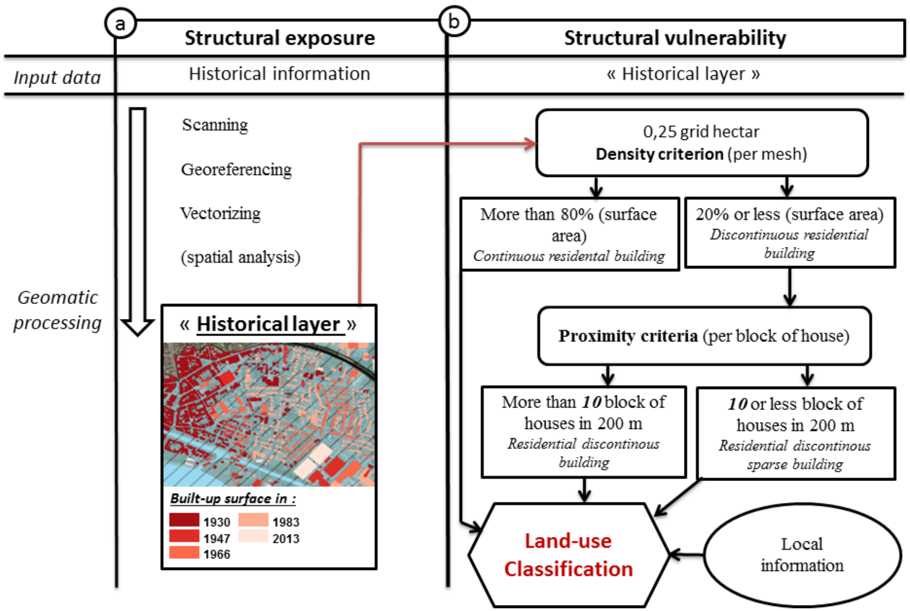


**Figure 6.** Evolution of land use: **(a)** structural exposure; **(b)** structural vulnerability.





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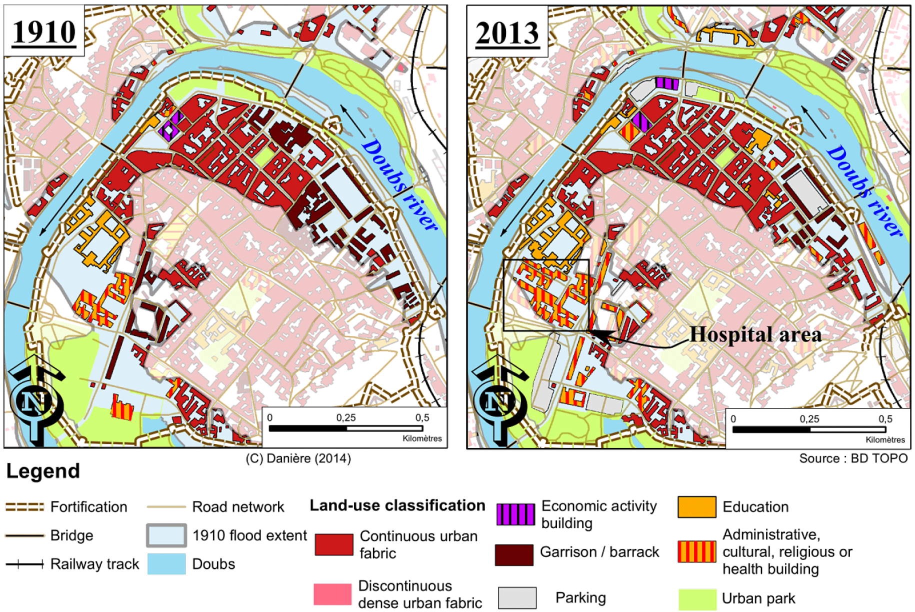


**Figure 7.** Land use and occupation within the 1910 flood extent in Besançon: **(a)** in 1910; **(b)** in 2013.

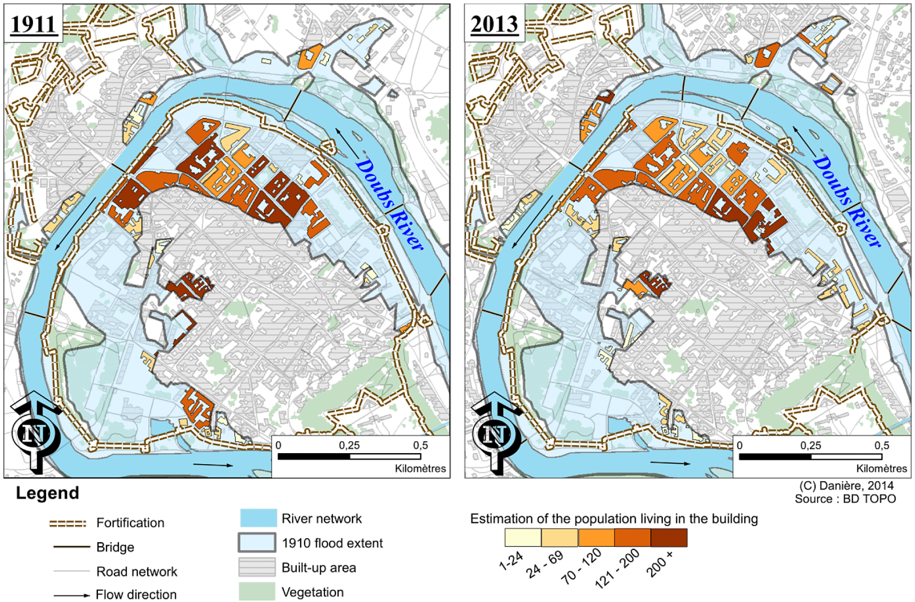


**Figure 8.** Estimated population per building within 1910 flood extent in Besançon: **(a)** in 1910; **(b)** in 2013. Some block of houses are depicted in only one map, because of land-use change. Non-residential blocks of houses are not taken into account here.





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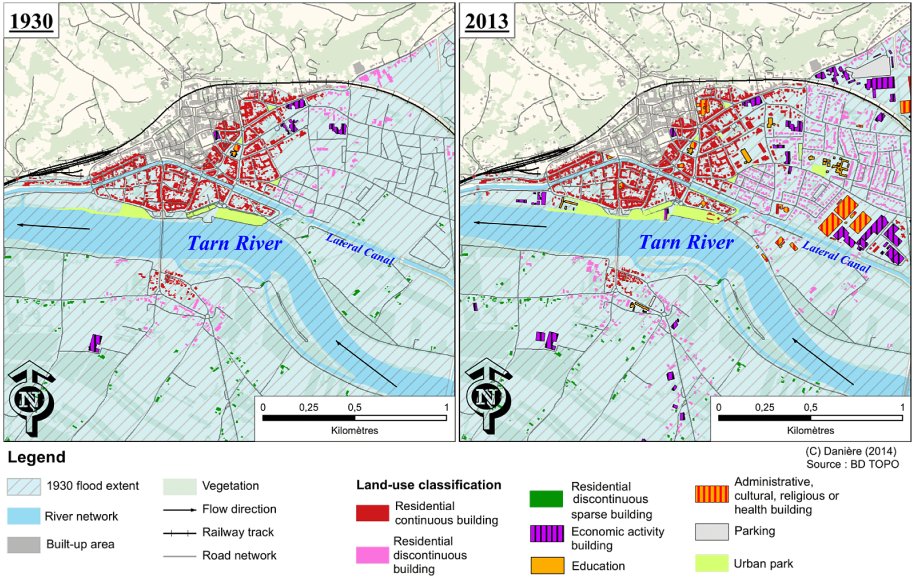


**Figure 9.** Land use and occupation within the 1930 flood extent in Moissac: **(a)** in 1930; **(b)** in 2013.





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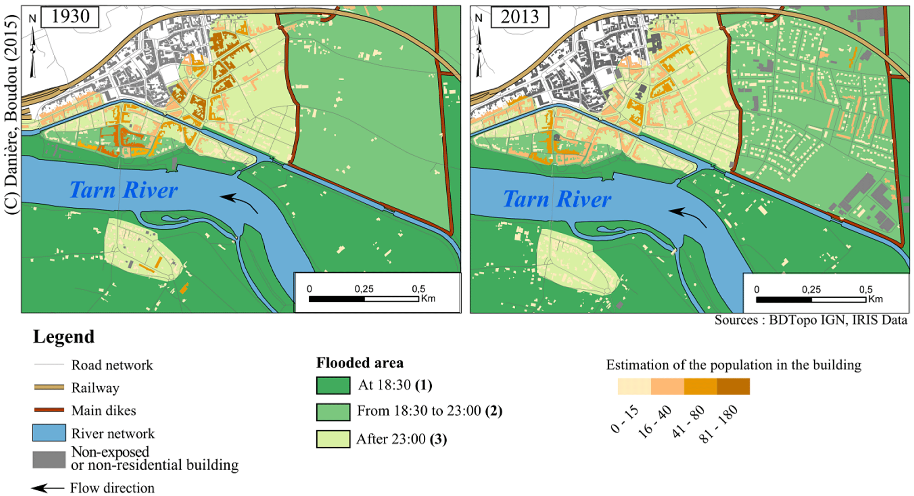


**Figure 10.** Estimated population per building within 1930 flood extent in Moissac: **(a)** in 1910; **(b)** in 2013.