Improving the understanding of flood risk in the Alsatian region by knowledge capitalization: the ORRION participative observatory

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Abstract. Despite the strong societal impact of natural hazards, their documentation remains incomplete, with only a few inventories exceeding the past two centuries. Surprisingly enough, this also applies to Europe, a densely populated territory, and to floods, which along with storms is the most common and damage-causing natural hazard in this area. In addition,

15 existing inventories have often been compiled by scientists and technicians and are used for risk management in a top-down manner, although the participation of all parties concerned has been recognized as a key factor for disaster reduction. To address this double paradox, the present article presents the regional flood risk observatory ORRION for the Alsatian region, northeastern France, and its very rich data content. Stemming from two successive interdisciplinary and transnational French-German research projects, ORRION was designed as a participative online platform where information is shared

20 between individuals, stakeholders, engineers, and scientists. This original approach aims at maximizing knowledge capitalization and contributes to building a common knowledge base for flood risk. ORRION is organized by events including all river floods that have likely arisen from a single synoptic situation. For each event, it documents information sources, date of occurrence, causes, and consequences in terms of damage and affected river basins and municipalities. ORRION contributed toward renewing our knowledge of flood hazard and risk in the target area. Notably, here, long

25 chronicles of floods are derived for 13 rivers, the Rhine and most of its main Alsatian tributaries, and for all Alsatian municipalities, most of them since the end of the 15th century, but over more than one millennium for the Rhine. Their main characteristics according to various typologies (seasonality, causes, severity, etc.) are analyzed. Major developments over the study period related to sources, land use, and/or climate change are identified. The advantages and limitations of the approach are discussed and the potential to expand both data exploitation and the building of common flood risk knowledge

30 are listed.

1. Introduct

Statistical analyses of long data series is a prerequisite for any effective management of natural hazards. They facilitate our understanding of the spatial and temporal dimensions of natural hazards, the relationship between intensity and frequency and, thus, help in evaluating reference scenarios for the definition of zoning maps or the design of defense structures. Today,

5   the need to capitalize historical information regarding natural phenomena and related damages over long time periods is therefore a priority among researchers and risk managers (e.g., Stediger and Cohn, 1986; Naulet et al., 2005; Paraystre et al. 2011). In order to complete instrumental series, generally limited to a few decades, historical analysis is increasingly used to reconstruct chronologies and understand the dynamics of the potentially damage-causing phenomena over several centuries. In practice, however, spatially and temporally comprehensive databases dedicated to natural hazards are relatively rare (e.g.,

10   Giacona et al., 2017), even in the case of hydrological risks (e.g., Guzzetti and Tonelli, 2004; Bradzil et al., 2006; Hilker et al., 2009; Martin ,2010; Wetter et al., 2011; Lang and Cœur, 2012).

From a different perspective, the information on natural hazards that is available to the public is generally summed up by researchers and/or managers. Furthermore, it more often than not remains limited to the mapping of hazard-prone areas (e.g., InfoTerre, Internet portal managed by the French Geological Survey) and to mentions of remarkable and/or severe

15   phenomena (e.g., French historical flood database, BDHI, http://bdhi.fr/; French avalanche database, Bourova et al., 2016). More rarely, comprehensive records in a given territory are offered (e.g., HISTRHONE, a historical database of floods in the lower Rhône River catchment, France, https://histrhone.cerege.fr/; French National Observatory for Natural Risks, Observatoire National des Risques Naturels, www.onrn.fr 2015). All these databases only partially contribute to detailed knowledge based on the memory of the past. Instead, information is transferred in a one-way top-down manner, from experts

20   to the public, to which "expert knowledge" (Höppner et al., 2012) is exposed without a clear logic of dialogue (Martin, 2006). Very few databases and platforms have been created to date as tools for sharing knowledge with mutual benefit between citizens, stakeholders, technicians, and scienti

Yet, the importance of public involvement and participation in environmental decision-making is now widely acknowledged and promoted, especially regarding risk management and/or knowledge capitalization (Scarwell and Laganier, 2004;

25   Kenyon, 2007; Koehler and Koontz, 2008; Fournier, 2010; Collombat, 2012; Wehn et al., 2015). Participative knowledge capitalization is particularly relevant in the European context of flood risk management. Indeed, many major floods have occurred in Europe during the past centuries, but also since the beginning of the 21st century (Hilker et al., 2009; Glaser et al., 2010; IPCC, 2014). These floods caused an estimated 150 billion euro of damage between 2002 and 2013 (Collet, 2014), costs that could increase in the near future due to global change (Glaser, 2014). As a consequence, the European Floods

30   Directive of 2007 – Directive 2007/60 / EC – jointly established by the European Parliament and the Council of the European Union proposed a paradigm shift (Albrecht, 2016; European Union, 2007). It introduced the need to reduce the consequences of floods using an integrated risk management approach that goes far beyond merely refined risk mapping.

Specifically, it is considered essential that the different actors, including the public, work together (European Union, 2007; Challies et al., 2016; Evers et al., 2016).

Fulfilling the wish of the European Floods Directive to establish closer cooperation between the European Union countries on this question, the French-German research programs ANR-DFG TRANSRISK (2008-2011) and TRANSRISK² (2014-

5   2017) involved researchers from both the University of Haute-Alsace Mulhouse (France) and the University of Freiburg-im-Breisgau (Germany). The interdisciplinary project team included hydrologists, climatologists, geographers, and historians. The TRANSRISK project thus made it possible to create a transnational database of historical floods in the south of the Rhine basin from the end of the 15th century to the present day. The data collected could then be used to address several scientific questions at different spatial and temporal scales. For instance, the data were used as a basis for a quantitative and

10   qualitative analysis of the floods having affected the major European rivers since the 16th century (Glaser et al., 2010). Also, Himmelsbach et al. (2015) conducted a study of the floods of the Rhine river and of its main French and German tributaries across the study area of the TRANSRISK research program. These authors presented a statistical summary of the flood chronology, determined the meteorological causes for the occurrence of the floods, and proposed a cartographic representation of some of the major floods. More specific studies proposed a flood classification model valid in the long

15   term, focusing on the specific analysis of the 1910 flood, used geohistorical data to analyze legal hazard mapping procedures and address the change in risk over time and space (Martin et al., 2015a; 2015b; 2017). Despite this broad outlook, however, a detailed analysis of floods that have affected all major rivers in this territory is still lacking.

The TRANSRISK² project expanded the study area. It also defined as a specific goal the strengthening of the collaboration between local authorities and relevant administrations in terms of flood risk management. More broadly, it aimed at

20   involving all the stakeholders concerned. During the project, the information required to implement Flood Risk Prevention Plans (PPRI), Flood Prevention Action Programs (PAPI), and Local Flood Risk Management Strategies (directive 2007/60/EC) was provided to the services in charge of these programs. In return, the latter contributed to the database by providing feedback from their archives or from local populations.

It is in this context that the participative database ORRION (for Regional Observatory of flood risk) was launched. As a first

25   step, currently, it only considers the French part of the study area (e.g., the Alsace region within its 2015 administrative boundaries). This original initiative was elaborated with the dual objective of (i) making the information collected by the research programs available to everyone, and (b) gathering information from all those involved in the local risk area. Indeed, it is believed that by collecting the different types of knowledge (from experts, profane, administrative, and scientific), one can hope to achieve a global, integrated, approach to the risk problem (Decrop, 1997). The TRANSRISK² research program

30   aims, in particular, at anchoring the risk in its territory through the enhancement and sharing of local knowledge. It must be noted that this process, and especially the online and open access information, takes place in the context of a clear lack of public knowledge regarding flood risk in the Alsace region (Martin et al., 2015a). Indeed, during the national survey on risk perception carried out by the IFEN in 2005, Alsatian inhabitants demonstrated their singularity by declaring that, in their

opinion, earthquakes were the risks to which they were the most exposed (Roy, 2005). However, according to the Alsatian public authorities, flood risk (including urban runoff, flashfloods, and rising groundwater) is likely to affect more than half of the Alsatian townships, including the major cities of Strasbourg and Mulhouse, even though their city center has not been flooded since the end of the 19th century (Martin et al., 2017).

5   The current article presents this original approach, involving both the creation of a database within the framework of a basic research project and the process by which it has been made available to a wider public who can enrich it in return. To address the need for developing long territorialized hazard and risk chronologies, the proposed analysis uses the information gathered, making it possible to highlight the main characteristics of the floods that have affected the Alsace, mostly since the end of the 15th century, but even before that period for a few rivers, and over more than one millennium for the Rhine river.

10   After providing a brief overview of the territorial context of the study area, special attention is paid to presenting the data entered in ORRION as well as to the structure of the sharing platform. For detailed analyses, two specific classifications are proposed to further distinguish the floods based on the rivers that were affected and the damage reported. Simple statistical methods are then systematically applied to infer the main patterns in flood causes, consequences, spatial extension, temporal distribution, seasonality, etc. Further analyses at the scale of selected rivers and municipalities are also presented. All these

15   illustrate the potential of ORRION, both for providing useful data to risk managers and for further improving our geophysical and socioeconomical understanding of flood risk in the target area. 💬lly, the main outcomes, advantages, and limits of the work are discussed and further perspectives are suggested.

2. Description of the territorial context

The study area, the Alsace, is located in northeastern France, in the French part of the Upper Rhine Valley (Fig. 1). It

20   extends over 200 km between Saint Louis in the south and Lauterbourg in the north, with a width of around 50 km from the Vosges Mountains in the west to the Rhine in the east. The highest mountain is the Grand Ballon (1,424 m a.s.l.) and the average elevation of the Alsace plain is around 150 m a.s.l (from 300 m a.s.l. in the south to 110 m a.s.l. in the north), with a slight slope toward the Rhine. The area is under the influence of prevailing westerly winds, and the Alsace Plain is situated in the transition area of maritime to continental climate (Minářová, 2013). Topography has a strong effect on the spatial

25   distribution of precipitation. According to records from meteorological stations available at a daily frequency since ca. 1950 (for some even over a much longer period), the annual precipitation is around 2,200 mm.a-1 in the south of the Vosges Mountains and less than 550 mm.a-1 at Colmar, one of the driest regions in France. Precipitation is also heterogeneous within the Alsatian plain. The southern part of the plain has a high precipitation amount because of the Belfort Gap and the absence of mountain relief. This is the same in the northwestern part – the Alsace Bossue – where the Vosges Mountains are

30   lower. Precipitation levels reach a maximum in the spring and summer and a minimum in autumn and winter. Furthermore, the moist western air masses and the prevalent temperature conditions allow for the accumulation of a deep snow cover in

the Vosges Mountains in winter, but its seasonal developments are frequently perturbed by temperature oscillations around the freezing level, even at the highest elevations (Giacona et al., 2017). This makes rain-on-snow likely any time during winter and spring.

The Alsace has different soil types: loess and filtering soil (sands, gravels, and limes), among others, forming a mosaic pattern in the hillsides beneath the Vosges Mountains as a result of a complex structural geology with fractures and faults. This leads to a variety of landscapes and land uses: (i) forest in the mountain areas, (ii) vineyards on the hillsides beneath the Vosges Mountains, (iii) grain production (as a result of irrigation) and farming (south and northwestern parts) in the plain, and (iv) wetlands due to aquifers along the Rhine and in the "Ried." Also, the Alsatian hydrographic network is particularly dense. It is composed of two systems (Rhin and Ill rivers), which both flow toward the North. The Ill river flows into the Rhine in the north of Strasbourg. Because of the density of this hydrographic network, the low elevation, and the nature of the ground, the soils in the plain are regularly strained by water-logging (particularly in the wetlands located between the Rhine and the Ill rivers). Indeed, many rivers are affected by groundwater aquifers, in particular by the upper Rhine alluvial aquifer (Europe's most important due to its extent, depth, and volume of water stored) and smaller aquifers accompanying some of the major tributaries of the Rhine. Relationships between rivers and aquifers are thus also important. As a result of the diversity in the topography, climate, soil, and land-use conditions, a large number of hydrological process and flood types (localization, spatial extent, origin, duration, etc.) are likely to occur (Himmelsbach et al., 2015).

On the other hand, Alsatian settlements are ancient, population, is dense and urbanization is important in both the plain and the valleys (Alsace is the third French region in terms of population density and urbanization), especially along rivers. Indeed, watercourses were already used by proto-industrial activities (sawmill, mill, metallurgy, etc.) and then by industry, especially the textile and chemical industries. The more recent development of commercial/industrial zones in flood-prone areas is also significant, as is the simultaneous expansion of urbanization in areas now protected by dikes. Over a longer timeframe, until the 20th century, river correction and flood mitigation measures were specific and focused on main cities only. As an exception, the Rhine river channel has undergone considerable modifications since the middle of the 19th century in order to limit flow divagations. The presence of many stakes along the Rhine river as well as along its Alsatian tributaries makes them prone to more or less regular flooding. This has led to the existence of sources documenting past floods.

[Figure 1] Presentation of the studied area

3. Data and methods

3.1. From the TRANSRISK database to ORRION online

A large part of the information currently stored in ORRION comes from the database built during the TRANSRISK project using geohistorical methods. The latter compiles information derived mainly from the analysis of archives (departmental and

communal) as well as from scientific publications, local nonscientific literature, and a few newspapers. The research focused on the main rivers of the Alsace in France (Largue, Ill, Doller, Thur, Zecht, and Lauch) and of the Baden region in Germany (Wiese, Klemmbach, Kander, Neumagen/Möhlin, Dreisam, Elz, Schutter, and Kinzig) as well as on the Rhine river. The database contains more than 3,000 entries (for each watercourse, each flood counts as one entry) of varied magnitude and

5   extension. Most of these floods occurred between 1480 and 2015, although a few entries refer to even older floods. Details about the data, the sources, and the historical methodology can be found in Himmelsbach et al. (2015). The tambora.org database provides the data for the German part (Riemann et al., 2015; Glaser et al., 2016).

The TRANSRISK database was designed by researchers for academic purposes. In order to facilitate data sharing, it was decided to build a regional observatory for flood risk (ORRION). The ORRION website was launched in 2015 after its

10 conceptual phase and its construction during 2014. The design of ORRION was guided by a SWOT analysis of flood risk databases already existing at that time: the French National Observatory of Natural Risks, the French database on the Historic Flood Events (BDHI) built reference to the European Floods Directive, the database of the French *Restauration des Terrains en Montagne* services, and the Regional risk observatory in Provence-Alpes-Côtes-d'Azur Region (southeastern France). The last one, like our study case, is based not on the French national scale but a regional scale. However, all these

15 databases have a complex or unattractive interface and do not meet the essential requirement of our objectives. Indeed, in these examples, the collaborative aspect concerns government services only, *de facto* excluding citizens. On the contrary, the objective of the ORRION database was not only to make raw data on historical floods in Alsace region available to all stakeholders, but also to provide a tool allowing all types of actors to actively take part in the compilations of flood risk knowledge in a collective approach.

3.2. Structure of the ORRION website and presentation of the data

The website ORRION was designed in this sense in partnership with the company CYSTEME. To minimize management difficulties, it is not structured along the lines of a "classic" online database but is built on a CMS structure (WordPress type). It is composed of four main parts (Fig. 2). The homepage reflects the territorial anchorage of ORRION and provides information regarding local flood risk management procedures. A second page, called "overview," presents the research

25 program TRANSRISK (objectives and administrators of the website) and the main characteristics of floods that took place in the Alsace. The third section leads to the database itself. A general map localizes all the floods recorded in the area and gives access to detailed information. A contact form is accessible both on the "database" page and directly on the homepage. It allows anyone to contribute to ORRION's comprehensiveness by sharing their information and knowledge about floods in the target area. Of course, information provided this way by online contributors is crosschecked by administrators before it is

30 integrated in the database. As the website is intended to inform and to share information in the particular context of a cross-border territory, it has a bilingual presentation (French and German). With the same perspective of sharing, communicating, and informing, ORRION benefits from a link to a Facebook page intended to increase the visibility and the attractiveness of

the website, via, for example, the regular publication of photos (especially public contributions) or former postcards illustrating old floods. Finally, as confirmation of its territorial anchorage, since 2017, ORRION has provided information on its homepage regarding various ongoing local procedures related to flood risk management, information, and prevention.

In addition to the participatory nature of the database, three other important factors differentiate the ORRION and

5   TRANSRISK databases. First, the latter deals with the whole upper Rhine Valley (French and German sides), whereas ORRION focuses only on the French side. Second, supplementary research was carried out for ORRION in the departmental archives of the Bas-Rhin and of the Haut-Rhin, enriching the information on floods that occurred in particular during the 19th and 20th centuries. Third, data are structured by "*events*" in ORRION: Each event in the website corresponds, at the scale of the entire study area, to a set of local floods that likely resulted from the same meteorological drivers (same synoptic

10   situation, similar soil saturation state, etc.). This is why there are far fewer ORRION events than entries in the TRANSRISK database, where each river flood is a single entry. Specifically, each ORRION event includes all rivers where a flood occurred within the same time window of 10 days (the downstream travel time of the flood wave may take several days). As a consequence, an ORRION event may correspond to one river that overflowed in one specific location (or to a more generalized extent) or to a situation where water overflow has been reported for almost all major Alsatian rivers at the same

15   time and often at several locations along the rivers (Figs. 3-5). Note that, in addition to a variety of river flood types, ORRION also reports on some mass movements due to local storms and on floods by surface runoff or by rising groundwater. Here, however, we focus only on river floods, and thus the latter types of events have not been taken into account.

In ORRION, events were characterized as precisely as possible, taking into account the fact that descriptions in the historical

20   sources are largely heterogeneous, which makes it difficult to produce homogeneous data. Thus, for each event, different fields are filled in when the information is available (Fig. 2D):

-    Date of occurrence: day/month/year, month/year, or year;
-    Affected rivers;
-    Impacted municipalities;
25   -   Causes. For each event, one or several causes (if any) can be documented;
-    Damage types: human (i.e., with at least one person killed), material, functional, environmental, unknown. For each event, zero to four damage types can be documented;
-    And the complete quotes accompanied by their sources.

Moreover, the database structure allows one to include tables and photos via hypertext links (Fig. 2D). The indexing

30   facilitates searches by keywords (years, river names, municipality names, causes, and consequences). To this aim, lists of terms have been pre-registered in order to standardize spellings and denominations, and to speed up data entering and browsing. The way of quoting sources has also been harmonized. When the impacted municipalities are known, there are displayed on a map (from Google) that is attached to each event. This map indicates the global extension of each flood event, but not the exact location of the damage that occurred.

5   ### 3.3. Further filtering and additional event typo ies

For a more detailed analysis of this specific work, four additional filters were applied for all the ORRION data. First, this article does not consider low-magnitude events during which no river overflowed its banks. Such events were discarded. By contrast, every event where water overflow occurred for at least one river was retained, as we wanted the most exhaustive overview possible of each event. Hence, for each event, we distinguished between rivers where flooding without water

10   overflow was described (i.e., simply an "abnormally high" runoff) and rivers with water overflow. Second, this study deals only with floods from overflowing rivers and does not include surface runoff or rising groundwater. As a consequence, from the whole set of flood causes documented in the ORRION database, we retained only heavy rainfall, long-lasting precipitation, snow melting/thaw, ice jam, ice breakup, thunderstorm, and soil saturation. Third, only the municipalities where water overflow has been explicitly documented are studied. Moreover, these items are defined here according to the

15   list of Alsatian municipalities from the 2006 French National Statistical Institute (INSEE) inventory, knowing that some changes occurred over the long period covered by ORRION such as merging or name changes of a few municipalities. Fourth, the analysis is focused on 13 of the main Alsatian rivers: Sarre, Moder, Zorn, Bruche, Lièpvrette, Giessen, Fecht, Lauch, Thur, Doller, Largue, Ill, and Rhine. To account for ORRION events that do not correspond to these rivers, "other" and "unknown" categories were added. The "other" category includes two types of rivers:

20   -   Tributaries of the main rivers mentioned earlier;
     -    Some major rivers for which fewer than 10 floods are known in ORRION and for which a specific analysis would
          not have been relevant.

In addition, two further classifications of the events were implemented. The first concerns the hydrological configuration of the event: (i) type R: only the Rhine river is concerned; (ii) type T: one or several Alsatian tributaries of the Rhine are

25   concerned, but not the Rhine itself; (iii) type RT: both the Rhine and at least one of its Alsatian tributaries are concerned.

The second classification concerns the severity of the events, taking into account both their spatial extent and the documented damage. Himmelsbach et al. (2015) proposed a classification of flood severity for TRANSRISK events, taking into account the same criteria, plus secondary and tertiary parameters such as the duration of the flood or the mitigation strategies that were implemented. The scale of Himmelsbach et al. (2015) has three levels ranging from "small flood" to

30   "extreme/supra-regional flood." However, this scale could not be used. For our events, the sources do not often allow the necessary secondary and tertiary criteria to be identified. Indeed, since our study covers a multisecular period, the available data are disparate, both qualitatively and quantitatively. The corpus of events is thus affected by different major types of heterogeneity (Martin et al., 2015): the nature of the sources evolves in time and space and the mass of documentation tends

to increase with time. Moreover, quantitative data are scarce. The classification must therefore be based on qualitative elements easily accessible in the archives over the entire study period. As the sources are essentially related to damage, they generally indicate, in a more or less detailed manner, the consequences of the floods. It is therefore possible to classify past events according to the damage described (Table 1). We distinguished three classes of damage according to the

5 consequences observed on the natural environment, on infrastructures, as well as on property and people. The level of damage was then coupled with the spatial extent of the floods (local or regional, taking into account both the number of impacted rivers and municipalities). With this simple multi-criteria approach, we distinguished four classes of event severity (Table 2). Such a classification could be applied to three quarters of the studied ORRION events. For the other ORRION events studied here, the severity class is considered as unknown (Table 3). This classification approach is robust because the

10 classification result is the same regardless of whether the spatial extension or the level of damage is considered first.

Type of stake	Null to minor damage	Moderate damage	Major damage
Environmental	Overflowed agricultural and forested areas (near rivers)	Vast overflowed areas of agricultural and/or wooded land	Vast overflowed areas of agricultural and/or wooded land; crop destructions
Functional		Road traffic cutoffs (roads under water); path deterioration	Destruction of a large number of dams, dykes, bridges, and/or roads
Material		Damage to infrastructures located close to rivers: mills, dams (gaps, holes, erosion, etc.), footpaths, etc.	
Human		Single casualty (death)	Several casualties (death)
Urban area			Water penetrating in urban areas: flooding of roads, basements, and companies. Damaged or destroyed buildings
River bed			Important morphodynamic process (significant changes of the river bed)

Table 1: Grid used to discriminate observed damage in three levels. Five types of stakes are considered, and for each of them the level of damage is identified (consequences increase from one damage level to another). The retained damage level for the event is the strongest among the different types of stakes.

Damage level	Null to minor		Moderate		Major		
	0		1		2		
Spatial extension	Local	Regional	Local	Regional	Local	Regional	Regional Plus
	0	1	0	1	0	1	2
Total score	0	1	1	2	2	3	4
Class	I	I	I	II	II	III	IV

Table 2: Multi-criteria severity scale for flood events. Classification is made according to (1) the level of damage evaluated as detailed in Table 1, (2) the spatial extension.

Class I, "small-sized events," includes floods with a total score of 0 or 1 (Table 2). It corresponds to local events that had no impact to moderate impact and to more regional events that had no impact or low impact. Class II, "medium-sized events," comprises events with a total score of 2. It includes two types of floods: those that caused significant damage but occurred very locally or regionally, and those that caused moderate damage but had a regional extension. Class III "large-sized events" brings together the events with a total score of 3 and corresponds to regional floods that have caused extensive damage. Within this third class, we identified a class IV of "extreme-sized events" corresponding to events that impacted at least 20 municipalities ("Regional Plus" level). Note that it is possible to identify these biggest events only over the last two centuries because the sources are not detailed enough to make comprehensive lists of affected municipalities for older events. Therefore, the fourth class is not set up as an independent class, but rather as a product of the third class. Hence, in the following analysis, all class IV events are included in class III, which makes the chronology of class III events *a priori* more homogeneous in time.

3.4. Statistical analyses

The complete data set of studied ORRION events was analyzed through a comprehensive set of basic statistical methods in order to identify the major spatiotemporal patterns of flood hazard and risk. For each event, each categorical variable (causes, damage types, hydrological configuration, and severity class) was coded in terms of presence/absence. Presence/absence codes were also given for each event in all municipalities (the 2006 Alsatian ones from INSEE) and rivers under consideration (the Rhine and the 12 tributaries we consider). For the rivers, distinct codes were given, depending on whether water overflow was documented or not. This coding step led to a data set from which deriving chronologies for the different types of events, rivers, and municipalities was straightforward. Also, visualization and analysis of the spatial characteristics of each event under a GIS environment was possible (Figs. 3-5).

All correlations between variables, rivers, municipalities, etc. were evaluated with the classic Pearson coefficient, whose significance was systematically tested with a Student test. Statistical significance was set at 0.05. Seasonality was studied for

the different event types on the basis of the interannual monthly distribution (percentage of events having occurred each month). Finally, time trends in the different chronologies were highlighted by evaluating 51- and 31-year moving averages in annual counts. For an easier visual interpretation, these moving averages have been rescaled on the corresponding plots. This was done by multiplying, for each series, the moving average values by the ratio between the raw annual count standard deviation and the moving average standard deviation.

4. Results

4.1. Overview

The corpus comprises 366 events that occurred between the years 886 and 2014. In total, 382 Alsatian municipalities were impacted at least once (Fig. 6). Of these, 19 experienced at least 10 events, among which four municipalities stand out: Strasbourg with 48 events, Mulhouse with 36 events, Colmar with 29 events, and Illfurth with 24 events (Figs. 6, 7F). Overall, the impacted municipalities are logically mostly located along the Rhine river and its tributaries, the Ill river, and the smaller rivers flowing down from the Vosges mountains. Also, most of them are located in the south of the study region. Events are mentioned by one to 324 sources (the latter for the September 1852 event). Two thirds of the events are documented by two or more sources. The events mentioned by a large number of sources are floods that caused damage (especially affecting humans) and that had a large spatial extension. Indeed, all damage types are positively correlated with the "source number" variable. Specifically, the Pearson correlation coefficient is +0.26 with the human damage presence/absence variable, non-zero at the 0.05% significance level (in what follows, only such significantly non-zero correlations are reported and discussed). There is also a very strong correlation between the source number variable and the extreme-sized events (class IV) and large-sized events (class III) variables (Pearson correlation: +0.56 and +0.29, respectively). Finally, it should be noted that the events mentioned by a large number of sources affected both the Rhine and its tributaries in particular (Pearson correlation with RT type: +0.27).

[Figure 6] Total number of flood events per municipality

4.2. Well-identified causes and consequences

Most of the analyzed events can be attributed to heavy rainfall (50% of the known values), snow melting/thaw (37%), long-lasting rainfall (32%), and thunderstorms (14%). Soil saturation, ice breakup, and ice jam were more rarely involved, for 7%, 5%, and 3% of the events, respectively (Table 3). Several causes (up to four) could be involved in a single event. For ca. 20% of the events, at least two causes could be documented, which represents a little less than a half of the events for which at least one cause could be identified (Fig. 7A).

		Number of events	Percentage of events (excluding unknown values)
Total		366	1
Causes	Ice breakup	10	5%
	Ice jam	5	3%
	Snow melting/thaw	71	37%
	Heavy rainfall	95	50%
	Thunderstorm	26	14%
	Long-lasting rainfall	62	32%
	Soil saturation	13	7%
	Unknown	175	/
Consequences (damage types)	Environmental	199	68%
	Functional	207	70%
	Human (at least one person killed)	31	11%
	Material	189	64%
	Unknown	72	/
Severity classes	Class I	83	36%
	Class II	71	31%
	Class III	77	33%
	Class IV	13	6%
	Unknown	122	/
Hydrological configurations	Type R (Rhine river alone)	42	13%
	Type T (Alsatian tributaries of the Rhine river only)	208	65%
	Type RT (both the Rhine river and its Alsatian tributaries)	72	22%
	Unknown	44	/

Table 3: Characterization of the ORRION events according to their causes, consequences, severity class, and hydrological configuration. Please refer to text and Tables 1-3 for a full definition of the different categories.

Moreover, the high-severity events (class III) mainly occurred during specific conditions: snow melting/thaw, heavy rainfall, and soil saturation (Pearson correlation: +0.35, +0.29, and +0.24, respectively). Also, the most severe events were due to a combination of unfavorable elements (Pearson correlation: +0.51 and +0.29 between the variables class III and class IV and the number of causes, respectively).

5 Flood events generated all kinds of damage: human, material, functional, and environmental (Table 3). Over the entire study period, 70% of the events (known values) led to functional damage (mostly road being cut off), 68% to environmental damage (mostly flooding of agricultural lands and forests), and 64% to material damage (mostly destruction of buildings and bridges). In total, 11% of the recorded events killed at least one person; 19.7% of the events had consequences that were not fully documented. Most of the events (51.1%) caused several types of damage and for 5.5% of the events, all four damage 10 types were documented (Fig. 7B).

[Figure 7] Characterization of the interannual distribution of events

4.3. Spatial extension: from local to widespread events

The extension of the events was often local. Indeed, 44% of the events involved only one river among the 13 we specifically 15 studied. In this case, by definition, overflow would have occurred for the river. However, single events sometimes had a much larger extension, with the two largest events affecting up to 12 of our 13 rivers (December 1947 to January 1948 and January 1955). For such events, rivers with and without overflow were distinguished, leading to specific distributions of number of rivers per event with and without overflow (Figs. 7 C-E). Regarding the hydrological configuration (Table 3), the recorded events mostly affected only the Alsatian tributaries of the Rhine (type T, 65% of the events), and, to a lesser extent, 20 both the Rhine and its Alsatian tributaries (type RT, 22%). The Rhine alone (type R) is documented to have been involved in only 13% of the events for which this typology could be determined.

In detail, for our 13 main rivers, between 15 and 163 events are known (considering floods with and without overflow; Table 4). The Ill river leads, with 163 events, followed by the Rhine river with 103 events, and the Largue river with 76 events. Extensive research was not carried out for the Sarre and the Lièpvrette rivers. This explains, at least partly, the smaller 25 number of events for these rivers, respectively, 15 and 19. However, the distinction between flood with and without overflow is important. The proportion of floods without overflow is, for some rivers, ~~very~~ high in comparison with the total number of floods. This is notably the case for the Rhine river, for which around 42% of the recorded events correspond to floods without overflow, and, even more so, for the Bruche river, for which this proportion reaches 73%.

Some rivers tend to flood simultaneously (i.e., during the same events), or, on the contrary, at distinct times (i.e., during 30 different events). This can be simply assessed by correlations between the presence/absence variable sequences (Table 5). Thus, the Sarre river tends to flood with the Moder, the Giessen, the Zorn, and the Bruche rivers (Pearson correlation: +0.45,

+0.32, +0.44, and +0.27, respectively). This makes sense since all these rivers are located in the north of the Alsace (Fig. 1). On the contrary, the Rhine and the Largue rivers tend to flood during distinct events (Pearson correlation: -0.14).

Even if more than two thirds (68%) of the events affected only one municipality, the flood that occurred in February 1958 impacted up to 89 municipalities (Fig. 7F). In all, 31 events (8.5%) impacted more than 10 municipalities, among which 13

5   events (8.5%) affected more than 20 municipalities, and four (1.1%) more than 40 municipalities. The latter group of events correspond to the floods of December 1947 – January 1948, 17 September 1852, December 1919 (Fig. 5B), and January 1882. There was a significantly positive correlation between 16, 11, and 4 municipalities and the variables "material damage," "functional damage, and "environmental damage," respectively, among which the municipality of Illhaeusern (Fig. 1) appears in every case (Pearson correlation: +0.16, +0.16, and +0.18, respectively). This identifies the municipalities more

10   prone to the respective damage types, and Illhaeusern as the municipality that suffered the highest damage, apart from casualties. The latter point may be related to the fact that Illhaeusern is often affected by floods of the Ill river, which are rather "slow" floods, so that people have time to escape and are used to doing so.

	With overflow in the considered river	Without overflow in the considered river	Total (with and without overflow)
Sarre	10	5	15
Lièpvrette	13	6	19
Lauch	19	7	26
Moder	19	7	26
Giessen	17	11	28
Zorn	11	21	32
Doller	34	11	45
Fecht	37	8	45
Thur	35	12	47
Bruche	16	43	59
Largue	57	19	76
Rhine	60	43	103
Ill	146	17	163
Other known rivers	54	21	75
Unknown rivers	85	6	91

Table 4: Number of events per river. The 13 rivers for which at least 10 events with water overflow were documented are

15   listed. ORRION also documents flood events (with and without water overflow) having affected other known rivers, as well as rivers that could not be identified in the available sources.

	Sarre	Lièpvrette	Lauch	Moder	Giessen	Zorn	Doller	Fecht	Thur	Bruche	Largue	Rhine	Ill
Sarre	**1.00**	**0.21**	0.06	**0.45**	**0.32**	**0.44**	0.06	0.06	0.05	**0.26**	0.00	0.00	-0.01
Lièpvrette	**0.21**	**1.00**	**0.32**	**0.23**	**0.40**	**0.28**	**0.32**	**0.29**	**0.28**	**0.34**	-0.03	**0.13**	**0.14**
Lauch	0.06	**0.32**	**1.00**	0.09	**0.24**	**0.14**	**0.35**	**0.41**	**0.40**	**0.23**	0.02	**0.14**	**0.20**
Moder	**0.45**	**0.23**	0.09	**1.00**	**0.37**	**0.61**	**0.20**	**0.13**	0.09	**0.39**	0.05	0.10	0.04
Giessen	**0.32**	**0.40**	**0.24**	**0.37**	**1.00**	**0.42**	**0.33**	**0.24**	**0.23**	**0.47**	**0.11**	0.10	**0.18**
Zorn	**0.44**	**0.28**	**0.14**	**0.61**	**0.42**	**1.00**	**0.27**	**0.21**	**0.20**	**0.50**	0.08	0.04	**0.17**
Doller	0.06	**0.32**	**0.35**	**0.20**	**0.33**	**0.27**	**1.00**	**0.39**	**0.43**	**0.27**	0.05	0.05	**0.25**
Fecht	0.06	**0.29**	**0.41**	**0.13**	**0.24**	**0.21**	**0.39**	**1.00**	**0.40**	**0.32**	0.03	**0.14**	**0.24**
Thur	0.05	**0.28**	**0.40**	0.09	**0.23**	**0.20**	**0.43**	**0.40**	**1.00**	**0.24**	0.09	**0.14**	**0.25**
Bruche	**0.26**	**0.34**	**0.23**	**0.39**	**0.47**	**0.50**	**0.27**	**0.32**	**0.24**	**1.00**	0.07	**0.20**	**0.26**
Largue	0.00	-0.03	0.02	0.05	**0.11**	0.08	0.05	0.03	0.09	0.07	**1.00**	-0.14	**0.11**
Rhin	0.00	**0.13**	**0.14**	0.10	0.10	0.04	0.05	**0.14**	**0.14**	**0.20**	-0.14	**1.00**	0.05
Ill	-0.01	**0.14**	**0.20**	0.04	**0.18**	**0.17**	**0.25**	**0.24**	**0.25**	**0.26**	**0.11**	0.05	**1.00**

Table 5: Pearson correlations between individual rivers by event presence/absence sequences. Events with and without water overflow are considered together. Bod values are significantly non-zero at the 0.05 significance level.

4.4. From low to exceptional severity

In all, 231 events (63%) could be classified according to their severity following our classification approach (Table 3): 36% (of the known values) in Class I, 31% in Class II, 33% in Class III, among which 6% in class IV. Our three main classes are thus more or less balanced. As expected, the 13 events identified as Class IV events (they affected at least 20 municipalities) all occurred since 1801. Specifically, these are: December 1801 – January 1802, January 1855, Mai 1856, February 1860, January – February 1862, February 1877, January 1910, February 1958, and February 1990, and the four events that affected more than 40 municipalities listed earlier.

High-severity events correspond generally to the configuration "Rhine and its Alsatian tributaries – RT" (Pearson correlation with this configuration: +0.43 for Class III and +0.32 for Class IV). On the contrary, the correlation is significantly negative with the configurations "Rhine alone – R" (Pearson correlation: -0.22) and "Alsatian tributaries alone – T" (Pearson correlation: -0.23). Symmetrically, low-severity events are more strongly related to the configuration "Rhine alone – R" than to the configuration "Rhine and its Alsatian tributaries – RT" (Pearson correlation: +0.27, and -0.30, respectively). This reflects the contribution of the spatial extension, and especially of the number of affected rivers, to the severity classification. In addition, the greater the severity of the events, the higher the correlation with the existence of damage, which is also logical since this is an even more important factor in the classification of severity. Hence, there is a positive correlation

between Class III events and all types of damage (Pearson correlation higher than +0.26 for all kinds of damage), even stronger for functional and material damage (Pearson correlation: +0.32 and +0.42, respectively). The opposite is observed for class I events, for which the correlation is ~~very~~ significantly negative with functional and material damage (Pearson correlation: -0.38 and -0.51, respectively).

4.5. Seasonality

Overall, the analyzed events took place during throughout the year but they occurred mainly in winter (from December to March: 45.9 %), especially in December (12.8%) and January (13.6%, Fig. 15A). A second peak is found in July (6.5%). It should be noted, however, that the month of occurrence is not known for 21% of the events sample. Snow melting/thaw and thunderstorms are physically coherent, well-identified causes for these two winter/summer peaks (Pearson correlation: +0.32 and +0.31, respectively).

However, this global seasonal distribution of events hides large disparities between the rivers studied. The seasonal distribution of floods affecting only the Alsatian tributaries (T configuration) is comparable to the global distribution (Fig. 15D). This is not surprising since these T events comprise the majority of the total sample. Specifically, the winter months – December, January, and February – are predominant and a slight summer peak is observable. The Bruche river is an archetypal case of this seasonal behavior: about four fifths of all its flood events took place during the three winter months (especially in December, representing almost half of the total, Fig. 15E).

The seasonal distribution is very different for the Rhine river, whose floods occurred in July and August instead. However, this does not prevent the occasional occurrence of significant flooding at other times of the year, as was the case in mid-September 1852. No event occurred in April and October in the configuration "Rhine alone – R" (Fig. 15B). When considering the floods that affected the Rhine river (both "the Rhine alone – R" and "the Rhine and its Alsatian tributaries – RT" configurations), the seasonal distribution is a little more noisy but the seasonal trend remains more or less the same (no flood in April, maximum activity in July, Fig. 15C).

[Figure 15] Flood event seasonality (monthly distribution)

4.6. Temporal distribution of events over the study period

To date, events have been considered independently of their year of occurrence. We now analyze their temporal distribution over the study period by year of occurrence, which could be documented for all events.

Overall, recorded events are very sporadic until the middle of the 15th century. Before that, only one event per year occurred for a few years, often separated by many years without any event. January – February 1374 stand as an exception, with three events that all concerned the Rhine river. From the middle of the 15th century, there is more regular information about events and the long-term trends starts to emerge, with a first activity peak just before 1600. The long-term trend then shows a

significant decrease at around 1700, before a 150-year period of increased continuous and strenuous flood activity occurs, up to a peak in the middle of the 19th century. After this peak, the number of recorded events is significantly lower but activity remains strenuous up to the last 20-30 years during which the last flood activity peak occurred (Fig. 8). This global trend, however, contains differentiated temporal patterns such as the function of rivers, municipalities, and events types, which are analyzed in the next section.

The typology of the hydrological configuration provides the first level of detail (Fig. 9). The frequency of events affecting the Rhine alone (type R) decreased over the study period (Pearson correlation with time: -0.45). Indeed, such events almost disappeared over the second half of the 20th century. Before this period, type R events could be retrieved rather regularly, even in the High Middle Ages (nearly all of the oldest events in the global chronology are type R events). On the contrary, the number of events that affected only the tributaries of the Rhine (type T) tends to increase over time (Pearson correlation: +0.37). In more detail, regular but sporadic flooding of the Alsatian tributaries was documented between the end of the 15th and the 18th century. Subsequently, the type T record significantly increases, showing a 200-year period of higher activity (1800–2000) and a very pronounced peak over the last 20 years. Finally, the floods that affected both the Rhine and its Alsatian tributaries (type RT) are distributed sporadically between the end of the 15th century and the 2000s, but with a very marked event concentration during the 19th century, especially in the second half.

In the second step, we propose to look separately at each of the 13 rivers under study. The temporal distribution of events differs considerably from one river to another, especially if the distinction with/without overflow is included in the analysis (Figs. 10, 11). The Ill and, as mentioned earlier, the Rhine rivers are those for which the most continuous information is available over the entire study period, whereas for other rivers such as the Sarre, Moder, Zorn, Lièpvrette, and Giessen rivers, the first mentions that could be retrieved go back to the second half of the 18th century. Also, there is usually a maximum of one event per year, except for the Ill and, to a lesser extent, for the Rhine, for which there are regularly two or three records per year. This suggests a higher flood frequency in major rivers with regard to their tributaries. In terms of long-term trend, in addition to the difference between the record starting dates, the major pattern is the high activity phase around the middle of the 19th century already highlighted overall and for the type R – RT chronologies. It is remarkably visible, e.g., for the Liepvrette, Fecht, Thur, Doller, Ill, and Rhine rivers, with some slight delay from one river to another. To a lesser extent, the very recent increase over the last 20-30 years is also visible for different rivers, e.g., the Giessen, the Sarre, and, in an even more pronounced way, for the Largue rivers. Concerning floods with/without overflow, it is noticeable that some drastic changes in proportions occurred for some rivers. For instance, during the 20th century there are about 15 events for the Rhine river, but no more floods with overflow after 1940. For the Bruche river also, floods without overflow, more numerous in proportion through the recorded period compared with the other studied rivers, are especially numerous over the last decades. For most of the other rivers, however, proportions of floods with/without overflow seem to have remained rather stable over the last centuries.

In terms of severity class, the temporal pattern is not very different for classes I–III. One notes that the global increase over the study period is slightly more marked for Class III events (Pearson correlation with time: +0.17) than for other classes. In other words, and surprisingly enough, severe floods are not easier to retrieve than milder ones far back in the past. The presence of the high activity peak of the last 20-30 years in all classes I-III, and of the high activity peak around the middle

5   of the 19th century in classes I and IV, is also remarkable (Fig. 12).

[Figure 8] Chronology of all recorded events: annual distribution and smooth underlying trend

[Figure 9] Chronologies according to event typology

[Figure 10]: Individual chronologies for the 13 study rivers: events with and without water overflow (1)

10   [Figure 11] Individual chronologies for the 13 study rivers: all events and underlying smooth trend

[Figure 12] Chronologies according to the event severity class as defined in Table 1

One can also see changes in the cause of events (Figs. 13). For instance, except for one flood in the early 1940s, no event could be attributed to ice breakups since the 1860s (Pearson correlation between ice breakup and time: -0.16). Similarly, the

15   few events related to ice jam all occurred before the beginning of the 19th century. On the contrary, "heavy precipitation" and "soil saturation" tend to increase from the 18th century and even more so from the 19th century (Pearson correlation: +0.16, and +0.30, respectively). Also, over the very recent period, records of events attributed to thunderstorms have increased greatly (Fig. 7E). Hence, significant changes in event-generating conditions may have occurred over the study period and may partially explain the overall shape of the chronology of events and their decline over the different rivers in terms of

20   frequency, severity, and seasonality.

Finally, in terms of damage types (Fig. 14), as we move forward in time, environmental damage and functional damage are proportionally greater (Pearson correlation with time: +0.13 and +0.22, respectively), their time trend following more or less the overall trend. Human damage, however, occurred rather regularly throughout the study period. Events that killed at least one person are therefore proportionally lower in number for recent events than for older ones (Pearson correlation with

25   time: -0.14).

[Figure 13] Chronologies of events according to their causes

[Figure 14] Chronologies of events according to their consequences

4.7. Focus on individual rivers

30   From the large sample of studied events, refined analyses can easily be carried out to better understand the behavior of individual rivers. Two examples corresponding to two different flood contexts are presented here: the Ill river, which has its

source in the Alsatian Jura and extends over a large part of the Alsace, and the Thur river, an affluent of the Ill river flowing down from the Vosges mountains.

Floods of the Ill usually occur simultaneously with a large number of other rivers (Pearson correlation: +0.52 between presence/absence for the Ill river and the total number of rivers per event). Logically, they often occur at the same time as

5   those of its tributaries, especially the Lauch, Fecht, Doller, Thur, and Bruche rivers (Pearson correlation: +0.20, +0.24, +0.25, +0.25, and +0.26, respectively). Events have occurred more often in recent times (Pearson correlation with time: +0.28) and, with regard to the total sample, are more related to snow melting/thaw and heavy rainfall and less to thunderstorms (Pearson correlation: +0.24, +0.18, and -0.14, respectively). Flood events in which the Ill river was included have caused a lot of functional and, to a lesser extent, environmental and material damage (Pearson correlation between the

10   presence/absence of the event and of the corresponding damage: +0.37, +0.15, and +0.15, respectively). Finally, it should be noted that Ill floods correspond mainly to high-severity events (Pearson correlation with Class III and Class IV: +0.23 and +0.18, respectively). This is because the Ill flood often affects large areas of the Alsatian plain, leading to, e.g., numerous roads being cut off.

Floods affecting the Thur river generally also affect most of the other rivers (Pearson correlation: +0.58 with the total

15   number of rivers per event, +0.43, +0.40, and +0.40 with the Doller, Lauch, and Fecht rivers, respectively). These are also events known from several sources (Pearson correlation with the number of sources: +0.30), more related to snow melting/thaw (Pearson correlation, +0.22), and causing a lot of damage (Pearson correlation with the number of damage per event: +0.37), especially human and functional damage (Pearson correlation: +0.31 and +0.23, respectively). Thur floods correspond mostly to severe events, particularly of Class III (Pearson correlation: +0.40), having affected both the Rhine and

20   its tributaries (Pearson coefficient correlation with RT hydrological configuration: +0.31). Thus, the Thur floods are rather typical of those of the rivers flowing down from the highest part of the Vosges Mountains in terms of generating factors and they often cause significant losses.

4.8. Focus on individual municipalities

Similarly, a detailed analysis can be conducted at the scale of the Alsatian municipalities.

25   As an example, we focus here on the three major cities of the Alsace, distributed from south to north, and representing a variety of situations in terms of flood hazard and risk. Strasbourg is situated along both the Ill and the Rhine rivers, Mulhouse close to the Ill and Doller rivers, and Colmar close to the Lauch and Ill rivers (Fig. 1). The temporal distribution of the events shows a reduction of overflow frequency during the 20th century for the three cities, certainly related to, at least partially, increased mitigation efforts to reduce damage. The overflow frequency reduction is especially outstanding in

30   Strasbourg (only three occurrences since 1900) and took place later in Mulhouse (significant drop after 1950 only). Also, documented floods with overflow activity were particularly high in Strasbourg during the 19th century, whereas the rate has been rather regular in Mulhouse since 1500, and especially over the 1700-1950 period (Fig. 16).

More specifically, the events that affected Mulhouse impacted many other municipalities (Pearson correlation with the number of municipalities per event: +0.21), among which are Altkirch, Baldersheim, Brunstatt, Meyenheim, Réguisheim, Walheim, and even more often Sausheim, Logelheim, and Illzach (Pearson correlation: +0.20, +0.27, +0.21, +0.22, +0.25, +0.23, +0.30, +0.33, and +0.47, respectively). As expected, the corresponding events are mostly severe ones (especially

5   Class IV, Pearson correlation: +0.14), caused significantly more functional and material damage (Pearson correlation: +0.17 and +0.20, respectively), and were more often linked to ice jams (Pearson correlation: +0.15) than other events were. These significantly positive correlations between municipalities simply reflect a common location along the Ill and/or Largue rivers. In addition, Illzach and Sausheim have been put at higher risk by a discharge channel constructed to protect Mulhouse.

10   Likewise, the events that affected Colmar usually also impacted several neighboring towns (Pearson correlation with the number of municipalities per event: +0.14), including Holtzwihr, Merxheim, Ribeauvillé, Zimmerbach (Pearson correlation: +0.25, +0.25, +0.25, and +0.23, respectively), and even more often Illhaeusern (Pearson correlation: +0.40). These flood events were significantly more related to ice jams and long-lasting rainfall than the other events of the analyzed sample (Pearson correlation: +0.24, and +0.16, respectively) and they caused in particular functional damage (Pearson correlation:

15   +0.16). Among the events that affected Colmar, medium-severity events (Pearson correlation: +0.21) as well as type RT events (Pearson correlation: +0.14) are over-represented, whereas Class I events are under-represented (Pearson correlation: -0.25). Stronger positive correlations are seen with municipalities situated like Colmar along the Ill and Lauch rivers, or along the Ill and Fecht rivers, which is due to the fact that the hydrological regime of the Lauch and Fecht rivers is rather similar.

20   Finally, the events that affected Strasbourg also often involved Artolsheim, Benfeld, Boofzheim, Diebolsheim, Friesenheim, Gerstheim, Illhaeusern, Ostheim, Ostwald, Réguisheim, Saasenheim, and Schoenau (Pearson correlation: +0.23, +0.23, +0.23, +0.23, +0.23, +0.27, +0.25, +0.22, +0.24, +0.20, +0.23, and +0.23, respectively) during Class III and IV events (Pearson correlation: +0.30 and +0.24, respectively), and rarely during Class I events (Pearson correlation: -0.18). Strasbourg floods are generally well documented (Pearson correlation with the number of sources: +0.26), and often caused different

25   damage types (Pearson coefficient with the amount of damage: +0.28). They often match the RT typology, and hardly fit the T typology (Pearson correlation: +0.48 and -0.42 respectively). Stronger positive correlations between municipalities are seen for those situated either along the Rhine or along the Ill rivers.

[Figure 16] Chronologies per municipality

5. Discussion: floods in the Alsatian region as currently documented in ORRION

Owing to its particular hydrological, climatic, and topographic context and to its dense population (roughly two times the mean population density of France), the Alsatian region is ~~very~~ sensitive to flood risk, with large flood-prone areas and potentially disastrous consequences (people killed, buildings and/or crop destroyed, economic losses due to functional

5   damage, etc.) for the most intense events (high return period floods in single rivers and/or widespread events affecting a large number of rivers, up to almost all of the Ill – Rhine tributaries together). For this specific territory, the web platform ORRION documents floods in terms of sources, dates of occurrence, causes, and consequences. Most of the events have occurred since the end of the 15th century, but a few of them occurred earlier for distinct rivers, especially the Rhine, for which the time frame covered extends over more than one millennium.

10   This article has shown that information accumulated this way and its organization by event is sufficiently rich and convenient to significantly update what was known to date about floods in the greater Alsatian region (Himmelsbach et al., 2015; Martin et al., 2017 and previous work). Specifically, it allows us to complement the results already obtained at the much larger scale of major European rivers (Glaser et al., 2010) and for specific events in the database (Martin et al., 2010). For instance, comprehensive flood occurrence data are now available for many rivers and municipalities with a careful

15   distinction of floods with or without overflow, and of specific typologies regarding the hydrological configuration, causes, and severity of each event. The combination of these data with simple but systematic statistical analyses allowed us to document the flood hazard and risk for the study territory with unprecedented accuracy and exhaustiveness. For example, significant correlations that are generally easy to interpret could be provided between almost all the variables we analyzed (causes, consequences, severity class, season of occurrence, damage types, etc.).

20   In more detail, the Rhine river is known to be largely influenced by the Alps, where it has its source, and therefore has a nivo-glacial hydrological regime with high water in early summer. This is obviously consistent with the flood seasonality and causes documented by ORRION. On the contrary, the Alsatian tributaries are known to have their peak discharge generally in winter, and sometimes in summer, although in Alsace precipitation amounts are at a maximum in spring-summer. Again, this fits our results showing that the floods affecting the Alsatian tributaries have a bimodal seasonal

25   distribution, mostly due to snowmelt in the Vosges Mountains and to continuous precipitation (for winter floods) and to thunderstorms (for summer floods). These differentiated flood causes and seasonal distribution as a function of the hydrological configuration reflect the results obtained by Himmelsbach et al. (2015) with a smaller number of Alsatian rivers. Yet, the richest information in ORRION is related to the time-depths of the series, whose outcomes are summarized in the following sections.

5.1. Flood changes over time as a function of social and environmental factors

30   We indeed highlighted strong nonstationarity in the flood chronologies, at all spatial scales (rivers, municipalities) and for the different event typologies we considered. Explaining in detail all the patterns of changes in all the chronologies is beyond

the scope of this paper because the sources (in particular the way archives were created and analyzed), land use (including corrective measures for rivers), and climatic factors have undergone major changes over the study period, and all played a role (Martin et al., 2017). However, contextualizing the sources and the events is sufficient to understand the main effects underpinning our results.

5.1.1. Changes related to sources and documentation of past events

The way the search is conducted through the archives (systematic or not, etc.) influences the results. Thus, it is not relevant to look at trends before the end of the 15th century. The TRANSRISK research program begins its study at that time. Older records are periodic and generally attributed to indirect sources that have rarely been verified. It should also be noted that the systematic search in the archives focused on the 19th and 20th centuries only, a period that enjoys certain homogeneity in terms of production and conservation of archives (Giacona et al., 2017; Lang et al., 2003). However, some recent events are missing or incomplete in the ORRION database because documents related to these were not already available in the departmental archives. The floods of April and May 1983 were major floods indeed, but they appear in our chronology as Class III events only (10 impacted municipalities for both floods) because departmental archives are still incomplete for this recent period. Additional searches were conducted in the local press within the framework of TRANSRISK², generating a huge number of new data currently not integrated into the ORRION database. This is certainly the most important factor explaining flood nonstationarity in our chronologies. For instance, the slight (and counterintuitive) increase in the number of Class III events over time is certainly partly due to the more systematic research conducted over the last two centuries. Moreover, as already mentioned, the appearance of Class IV events at the end of the 17th century constitutes an artifact linked to our typology and to more incomplete and/or less detailed sources for the earlier periods. Hence, increasing patterns in Classes III and IV are partially related to an increase in sources simply meaning that more and more elements at risk were set up along rivers (vulnerability increase). Similarly, the apparently higher exposure to risk of the municipalities situated in the south of the studied region is, at least partly, linked to the fact that more research was done in this sector to retrieve old events than in the rest of the Alsatian region, especially for the Largue, Lauch, Fecht, and Ill rivers.

However, other societal factors also play a role, and our capacity to retrieve past events must be related to the cultural and political context. The study area has, for instance, faced three French-German conflicts between 1870 and 1945. During these 75 years, it changed its sovereignty five times, its administrative system, and its language. Such a history does not benefit the continuity of knowledge on flood risk. In addition to the fact that part of the information included in the archives may have been destroyed or lost, information is sometimes very hard to understand or interpret for the layperson: imprecise classifications, documents and press in German and in Gothic script, This especially applies to the German period between 1870 and 1918: although the Alsatian population faced the strongest floods of the last 150 years during that period (i.e., 1876, 1882, 1910, and 1919), these events remain largely unknown by the local French authorities today (Martin et al., 2015).

More generally, the process that transforms observations into sources depends on the relations between societies and their environment, in particular rivers. Sources are closely related to damage, but also to strategic and economic issues. Thus, because of the Rhine's strategic importance as a transport corridor since the 19th century (see below), floods without overflow were systematically documented during part of the 19th and 20th centuries and kept in the archives. This was not the case for the earlier period, where the Rhine was much less navigated. This explains the sudden increase in records of floods without overflow since the 19th century (Fig. 10M). Moreover, it should be noted that, in many cases, the floods we considered as "without overflow" correspond to sources with brief information only. This means that there is often doubt about the exact nature of the flood (with or without overflow). Hence, this information must be considered with extra caution. For instance, the great proportion of floods without overflow of the Bruche river is clearly an artifact directly related to the nature of the sources that could be analyzed (a large number of technical reports document each abnormally high runoff for this specific river).

5.1.2. Changes related to land use and risk management

The chronologies that go far back in time are those of the Rhine and the Ill rivers. Those of the smaller tributaries flowing down the Vosges mountains start much later. Events recorded are also more regular over time for the Rhine and Ill rivers. This can be partly linked to sociospatial dynamics. Indeed, most of the population of the region for a long time lived in the lowlands along the rivers, where a large number of elements at risk were thus located throughout the study period. On the contrary, the Vosges Mountains have always been less densely populated, thereby explaining the difference in the length and regularity of records.

However, until the 19th century, the Rhine river was characterized by a sinuous course formed of braided and anastomosed channels, with a very wide main bed that changed very often. Massive corrective works were then conducted to channel its course. This allowed for the economic development of the territories bordering the river, which became a major axis of goods circulation. Furthermore, this probably contributed to the drastic reduction of Rhine river floods at the turn of the 20th century (Tulla correction achieved in 1876, correction of the Swiss Jura rivers carried out between 1868 and 1891) and to their quasi-disappearance since the mid-20th century (construction of the Grand Canal d'Alsace between 1932 and 1959), especially regarding floods with overflow. A similar analysis can also be applied to other smaller rivers to explain certain major breaks that occurred locally at certain times points in the study period, and to major cities, where important works were carried out to reduce their vulnerability to flood. As a striking example, the absence of significant flooding affecting Mulhouse since the beginning of the 20th century may be related to the construction of the Ill river discharge channel completed in 1906, which has proven to be effective (Martin et al. 2015; Fournier and Holleville, 2016). The same holds true for Strasbourg, protected from any floods of the Ill river since the construction of a discharge channel in 1891. The old town of Strasbourg has not been flooded since 1882. Moreover, even if the flood of 1919 was probably the largest of the 20th century, the damage was extensive in the entire basin but not in Strasbourg.

5.1.3. Changes related to climate drivers

Climate factors were clearly not stationary over the study period spanning more than one millennium, and the way they have changed in the study area is now well documented (e.g., Glaser and Riemann, 2009; Zorita et al., 2010; Le Roy Ladurie, 2011; Glaser, 2013). How this may explain the changes in flood activity that we document remains difficult to determine.

5   This is especially true for the beginning of the study period, owing to the sparseness of the data at that time and the complexity of the combination of weather factors generating floods. However, the major climate change patterns of the past centuries are clearly visible in most of our chronologies. After the rather warm medieval period, the study area experienced the colds of the Little Ice Age (LIA) up to the second half of the 19th century (Grove, 1988; 2001), and is now affected by the recent anthropogenic warming occurring in the past few decades. The temporal distribution of flood causes reflects these

10   patterns of change: floods attributed to ice break up and ice jam have no longer been documented since the mid-19th century (except one event during the 1940s), which may simply result from the end of the LIA. Also, the recent warming may explain the concomitant drastic increase of floods due to thunderstorm.

Hence, if one puts aside the more or less continuous increase of sources over the study period, phases of high/low flood activity can roughly be related to the prevalent climate context. For instance, the first activity peak in our event chronology

15   (~1600) corresponds to the Maunder Minimum (coldest decades) of the LIA. Similarly, the second activity peak in the 19th century corresponds to the Dalton LIA minimum, quickly followed by its termination. Notably, many of the most remarkable floods of the Rhine river are concentrated during this short time period: 1851, 1852, 1872, 1876, 1876, 1877, 1881, and 188. Furthermore, documentation of this pattern for most of the Alsatian tributaries shows its robustness and other studies highlighted the pattern in other areas where a social explanation cannot be invoked (e.g., Wilhelm et al., 2013).

20   ### 5.2. Pros and cons of the data structure and chosen event typology

The space and time comprehensiveness of ORRION, and the easy browsing of the database allows information that is highly valuable for supporting risk management policies to be easily extracted and used. For instance, its original by-event organization facilitates the easy characterization of areas potentially threatened within a single meteorological situation, with a direct measure of the likelihood of different rivers flooding at the same time, a very valuable contribution to operational

25   risk management at the local scale. As a further example of its value, the database has already been mobilized for the positioning of flood marks in the framework of the French PAPIs (flood protection plans). It thus allowed local stakeholders, who had forgotten old and severe floods affecting rivers for which they had the risk management responsibility, to increase their knowledge about flood risk.

Yet, to build ORRION and further exploit and summarize the large number of data at our hand in this specific study, we had

30   to make stringent working choices and assumptions. For instance, we chose simple but robust classification schemes for the severity and hydrological configuration of events. These were shown to be sufficient to reach meaningful conclusions, but, clearly, they could be refined and reconsidered in further work. Also, our choices must be kept in mind when deriving

conclusions from our results. For example, our severity classification is strongly driven by damage, and the damage score we retain for an event is the one corresponding to the highest registered damage. This has the effect of smoothing potential spatial differences across the study area, especially for events of large extension.

Also, the distinction we made between floods with and without overflow was found useful but, in practice, it raises some
5   questions. Indeed, some floods caused damage without overflowing (to a mill in the main channel, for example). Since sources are mainly related to damage, this situation is found rather frequently. For a given event, we chose to define a flood as an overflow (i.e., in order to appear in the analyzed sample an event must include an overflow for at least one river). As a result, not all the damage currently in ORRION was taken into account in this study. Damage that occurred during events without known overflow was de facto excluded. Also, for the work done at the scale of municipalities, only overflows were
10   considered. Therefore, not all damage that occurred without overflow in a given municipality appears in the corresponding local statistics. The results we obtained regarding municipalities where thus highly dependent on the implementation of defense structures such as dykes, which make (theoretically) overflow much more difficult. This effect explains in part the temporal changes in the chronology of events for the Rhine river (Fig. 10M) and for the largest Alsatian cities (Fig. 16).

5.3. The participative choice: a long-lasting but rewarding effort

15   Given the now well-known limits of top-down approaches in the field of risk management, the TRANSRISK² research program focused on the implementation of a participatory approach. The ORRION database has been developed in this way, with the double objective of knowledge capitalization and sharing. The participatory dimension of the database remains for the moment somewhat weak, with only a small amount of the information currently in ORRION coming from the public. However, this is not surprising since many studies already highlighted the low public interest in natural hazard issues and
20   their management. These studies identified different factors influencing the active engagement of the public, such as "the direct experience of flooding," "education" and "knowledge," "the technical resources of the public," and "public perceptions of technical complexity related to hazard mitigation" (Koehler and Koontz, 2008; Kenyon, 2007; Godschalk et al., 2003). It has even been shown that, because the participative dimension is absent from the prevalent culture of flood risk management, a paradigm shift can be problematic in terms of method and/or practical implementation (Evers et al., 2016;
25   Ruiz-Villaverde and Garcia-Rubio, 2017; Hegger et al., 2013; Simonovic and Akter, 2006; Thaler and Levin-Keitel, 2016; Wehn et al., 2015). As a consequence, the participative approach remains uncommon (Jingling et al., 2010; Koehler and Koontz, 2008), and is even sometimes considered as responsible for generating tension between the actors concerned (Kuhlicke et al., 2016).

Hence, in practice, it is still largely "experts" who define the risk and the answers to be given (e.g., November et al. 2011),
30   thereby inducing a clear distinction between public knowledge and expert knowledge. In practice, often, at best an integration of local authorities and experts into the risk management process is aimed at. Even more simply, it is sometimes deemed sufficient to set up communication strategies to inform/raise public awareness of the risks involved (e.g., Dunbar,

2007; Kuhlicke et al., 2016) or to help it accept the management strategies defined by the experts (Hubert and De Vanssay, 2005; Vinet, 2010). Finally, when a participative approach is adopted, it usually consists in summing up oral memory or, more generally, in exploiting information produced by the public in a one-way movement in order to improve the mapping of a phenomenon or the crisis management (e.g., Kundu and Kundu, 2011). As an example, the citizens' natural risk

5 observatory of the French geological survey aims at collecting information from social media. Thus, few projects conceive the participative choice as a collaborative exchange and decision-making process where the different stakeholders and public involved fully contribute to the risk management process, from the definition of the problem to the answers to be given (Simonovic and Akter, 2006).

Despite these difficulties and the few successful participative experiences currently underway, the adoption of the ORRION

10 tool by citizens is fundamental given the currently poor documentation of extreme floods in the Alsatian region, and, more generally the weakness of the existing risk awareness schemes. This latter situation is certainly partly due to the particular historical context of the region, as mentioned earlier. Another reason may be that the last major flood occurred in 1990, almost 30 years ago, and therefore its memory has blurred with time. Indeed, things may have been different in the context of more frequent major floods or just after a disaster. For instance, during the June 2013 Pyrenees floods, researchers from

15 the University of Toulouse (France) issued a call for experiences (lived, felt, etc.) and testimonies, including photographs and videos, not only of the current event but also of older episodes. This call for contributions was successful as more than 5,000 photographs were collected (June 2013 Pyrenees' floods, http://cruespyr2013.canalblog.com).

Thus, the participative part of the ORRION is currently not perfect but it represents an encouraging start. The platform is now very well identified by local risk management actors, but some work remains to be done to involve the general public

20 more. To this aim, communication is clearly necessary to make more people aware of the existence of ORRION, of the reality of flood risk in the Alsatian region, and of the importance for disaster reduction that any information they have is made largely available on the platform. As an example of such actions, the Facebook page devoted to ORRION has helped greatly in increasing visibility among the 18-35-year-olds (more than 5,000 have seen a publication concerning the 1947 flood). Also, after a report in the local newspapers of the major flood of December 1947, 70 years after its occurrence, there

25 was an increase in public contributions to ORRION. In a similar spirit, a commemoration of the 1919 – 1920 extreme-size flood event for its centennial anniversary is now planned to remember the destruction the region suffered at that time and to highlight how difficult it would be to deal with a similar event today. Illustrative numerical simulations of the event and of its damage potential using the participative ORRION information as input and with results displayed and explained on the web platform are also envisaged. This would be a step further in the direction of a better sharing of risk knowledge between

30 citizens, stake-holders, technicians, and scientists, and may exemplify how exchanges between all these groups of people may lead to mutual benefits.

6. Conclusion and outlook

The European Flood Directive has published specific guidelines for disaster reduction. As a response to the expressed need of improving both the documentation of past events and the sharing of information between all parties concerned, this article has presented the regional flood risk observatory ORRION and its very rich data content. Grounded on two multidisciplinary research projects, ORRION has been designed as a participative online platform where knowledge capitalization and exchange are maximized. Hence, the uniqueness of ORRION is to be a collaboration, communication, and awareness tool. This article has shown that the data and original organization by events attest to the complex and specific historic situation of the Alsatian region that has undergone manifold political changes over the past few centuries. Consequently, the database helps to renew our knowledge of flood hazard and risk in the French upper Rhine catchment area, providing long spatiotemporal chronicles of floods for 13 rivers, and for all Alsatian municipalities, as well as their main characteristics according to various typologies (seasonality, causes, damage types, severity). It also helps identify the major changes and their social and environmental drivers throughout the study period.

However, only a rapid analysis of this abundant information was performed. Hence, further research could clearly exploit the data in many directions, for example, explicit statistical modeling with advanced nonseparable spatiotemporal covariance models instead of the rather simple descriptive techniques that were used in this work. Coupled with the diachronic analysis of land use, settlements, and practices, this may facilitate further understanding of the main pattern of change in flood risk, such as, e.g., the respective weight of climatic and social factors in the dramatic increase in flood activity that was identified in the first half of the 19th century. In parallel, using the information summed up in ORRION to drive hydrological and hydraulic simulations for the Rhine river and its main Alsatian tributaries may provide greater detail on the dynamic characteristics of the flood events themselves (response time of the watersheds, flooded areas and corresponding water depths, efficiency of existing or potentially new countermeasures for the hazard, etc.). This could be a valuable contribution to the improvement of current legal hazard and risk maps and to their necessary adaptation to ongoing climate and societal changes. All in all, the potential for both further geophysical inference and more operational outcomes is clear.

Concerning the data, some improvements are also necessary. The available information, although impressive, is certainly not exhaustive. Further browsing of archival documents, local press, and official documents initiated after disaster occurrences and integration of their output into ORRION are envisaged if the funds can be obtained. This would allow for better documentation of the Alsatian rivers that have not been studied so far because the number of flood events involving these rivers has not been regarded as representative enough of the physical reality of flood hazard and risk. In parallel, documentation of certain major events of the past such as the 1910 and 1919 floods could thus be improved. However, the main challenge in terms of data improvement is to promote database enrichment through its participative interface. The advantages and limitations of the participative approach have been discussed, highlighting its potential but also the difficulty of ensuring that the highest number of potential contributors take part. We sincerely hope that, thanks to devoted communication and dissemination actions, it will be possible to intensify this effort in the upcoming years.

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8. Data availability

5 All the data supporting this study can be freely accessed and browsed on the ORRION participative platform (http://orrion.fr/). Feedback and contributions are most welcome.

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Figure 1: Presentation of the study area.

Figure 2: ORRION user's interface (http://orrion.fr). A: homepage; B: presentation of the project and of the main characteristics of floods in the Alsace region; C: database's access page with a general map of all recorded events; D: example of an article corresponding to a specific event; E: contact form to post a participative contribution.
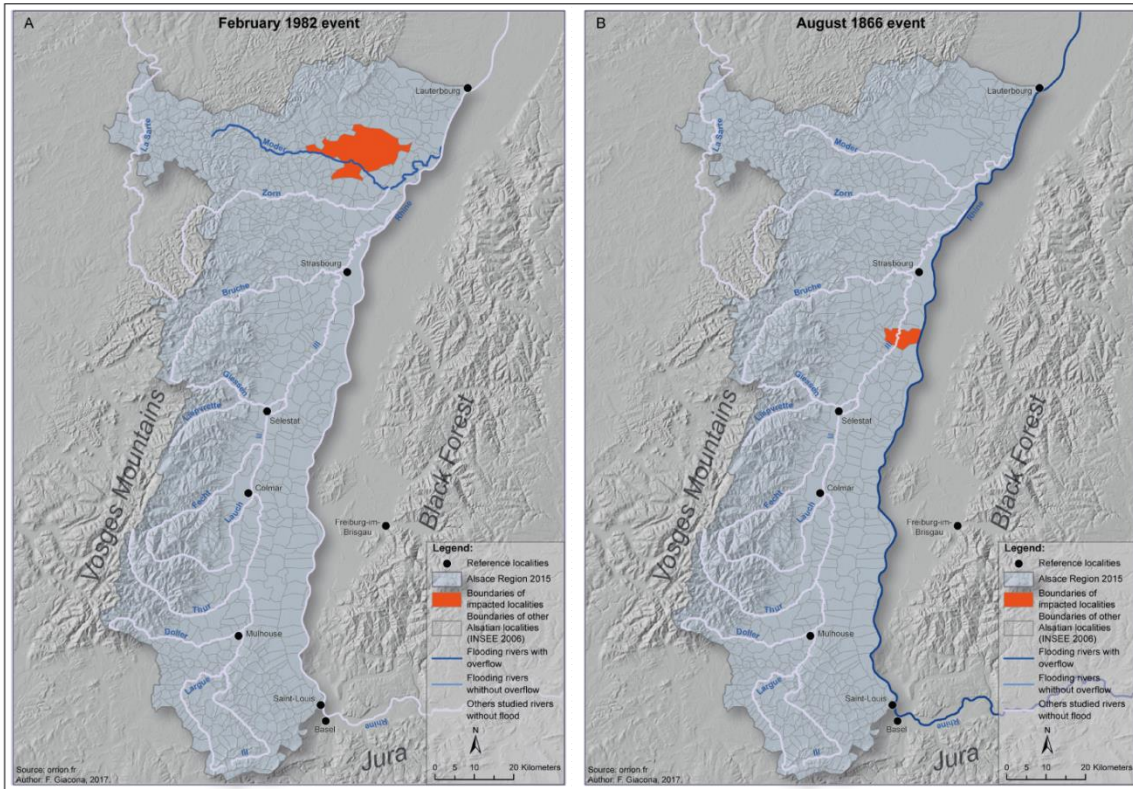
Figure 3: Maps of two class I events.

A: February 1982 event. "Alsatian tributaries of the Rhine river only – T" configuration. Extension score: 0. Damages score:
5   1. Overflowed Moder river caused functional damages and impacted one municipality. This event is attributed to snow melting/thaw and to long lasting rainfall. It is known from 1 source.

B: August 1866 event. "Rhine river alone – R" configuration. Extension score: 0. Damages score: 0. Overflowed Rhine river caused environmental, functional and material damages, and impacted 1 municipality. This event is attributed to long lasting rainfall and is known from 43 sources.
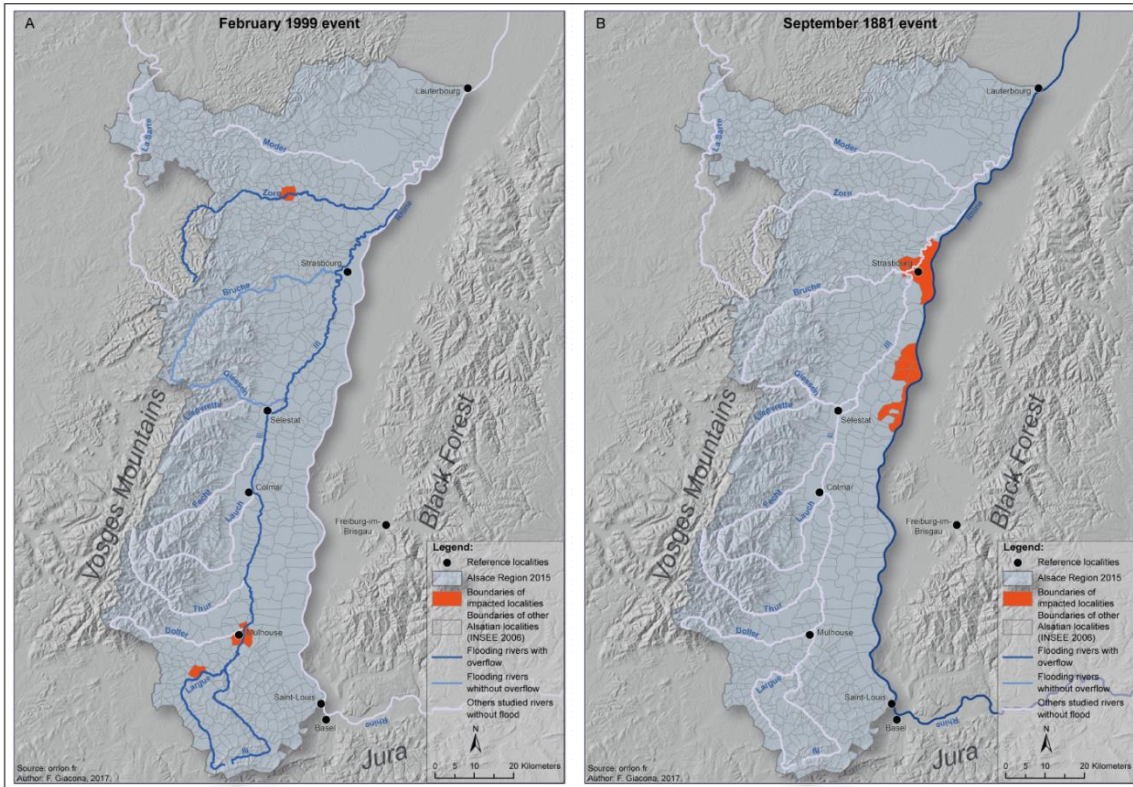
Figure 4: Maps of two class II events.

A: February 1999 event. "Alsatian tributaries of the Rhine river only – T" configuration. Extension score: 1. Damages score: 1. Overflowed Largue, Ill and Zorn rivers caused material damages and impacted 3 municipalities. Giessen and Bruche rivers were flooded without overflow. This event has unknown causes. It is known from 7 sources.

B: September 1881 event. "Rhine river alone – R" configuration. Extension score: 0. Damages score: 2. Overflowed Rhine river caused environmental, functional and material damages, and impacted 8 municipalities. This event is attributed to heavy rainfall and is known from 5 sources.
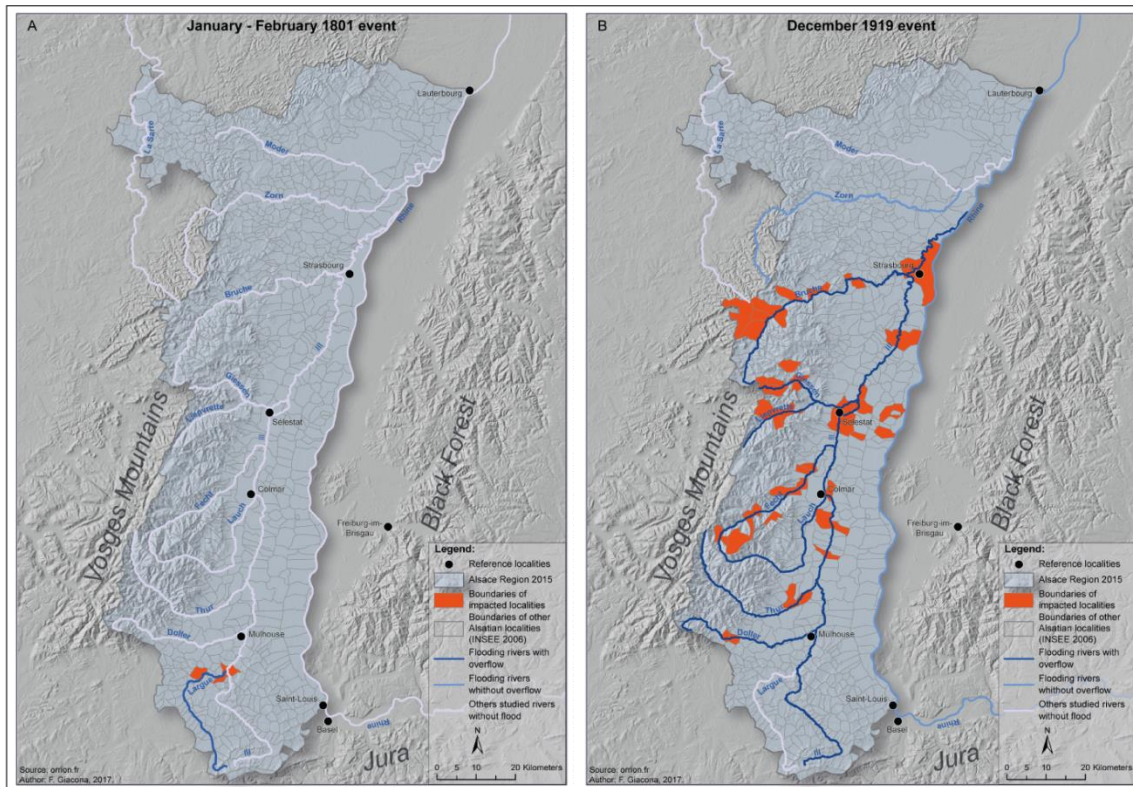
Figure 5: Maps of two class III-IV events.

A: January-February 1801 event. "Alsatian tributaries of the Rhine river only – T" configuration. Extension score: 0. Damages score: 2. Class III event. Overflowed Largue river caused environmental damages and impacted 5 municipalities. This flood is attributed to snow melting/thaw and to heavy rainfall. It is known from 1 source.

B: December 1919 event. "Rhine river and its Alsatian tributaries – RT" configuration. Extension score: 2. Damages score: 2. Class IV event. Overflowed Ill, Doller, Thur, Lauch, Fecht, Lièpvrette, Giessen, and Bruche caused human, environmental, functional and material damages, and impacted 45 municipalities. Rhine and Zorn rivers were flooded without overflow. This event is attributed to snow melting/thaw and heavy rainfall and is known from 61 sources.
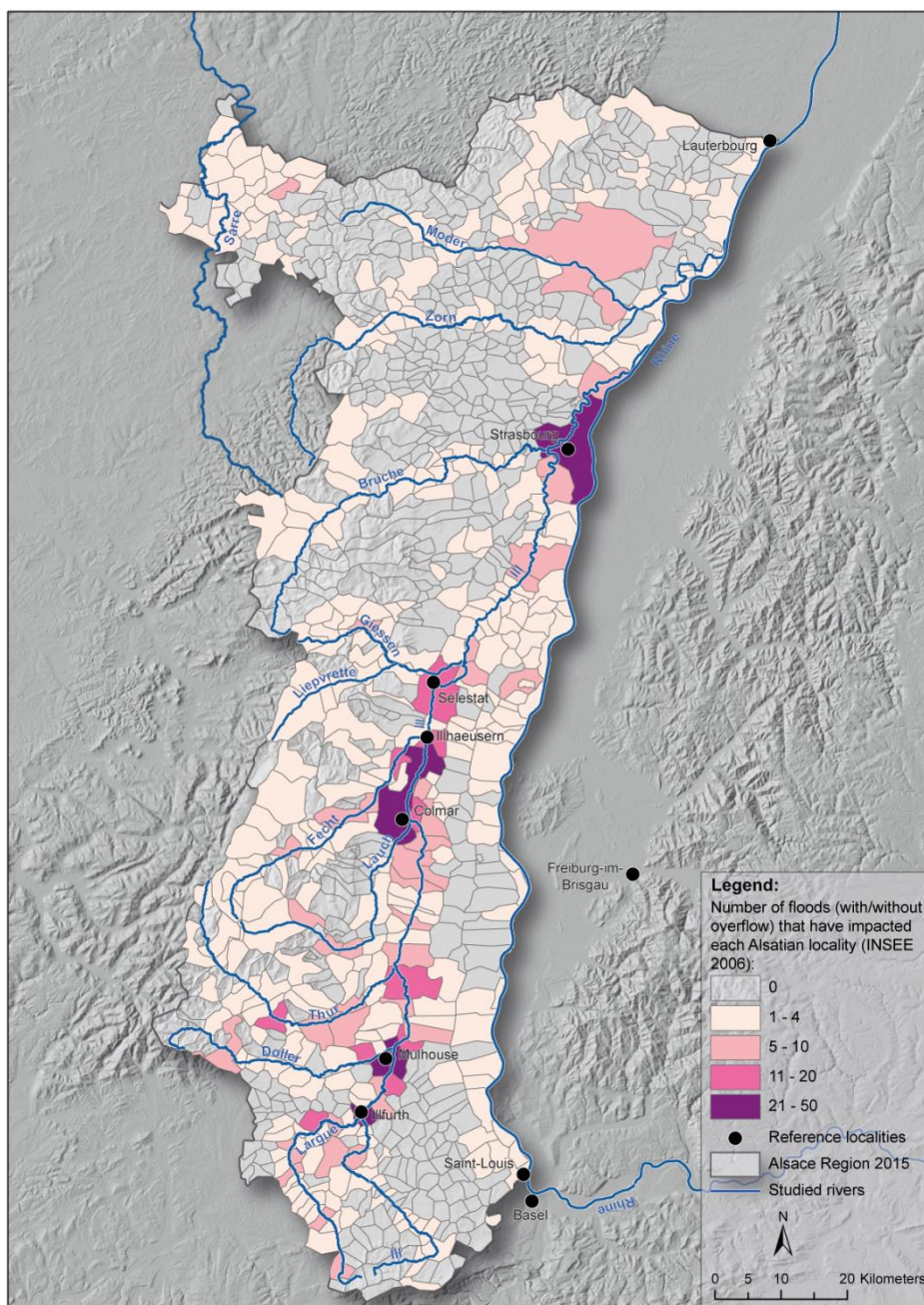
Figure 6: Total number of events per municipality. For each event, only the municipalities where water overflow has been reported are considered. Most of the overflows concern the 13 rivers specifically studied in this work, but a few correspond to other rivers (smaller rivers and/or rivers with less than 10 flood events in the ORRION
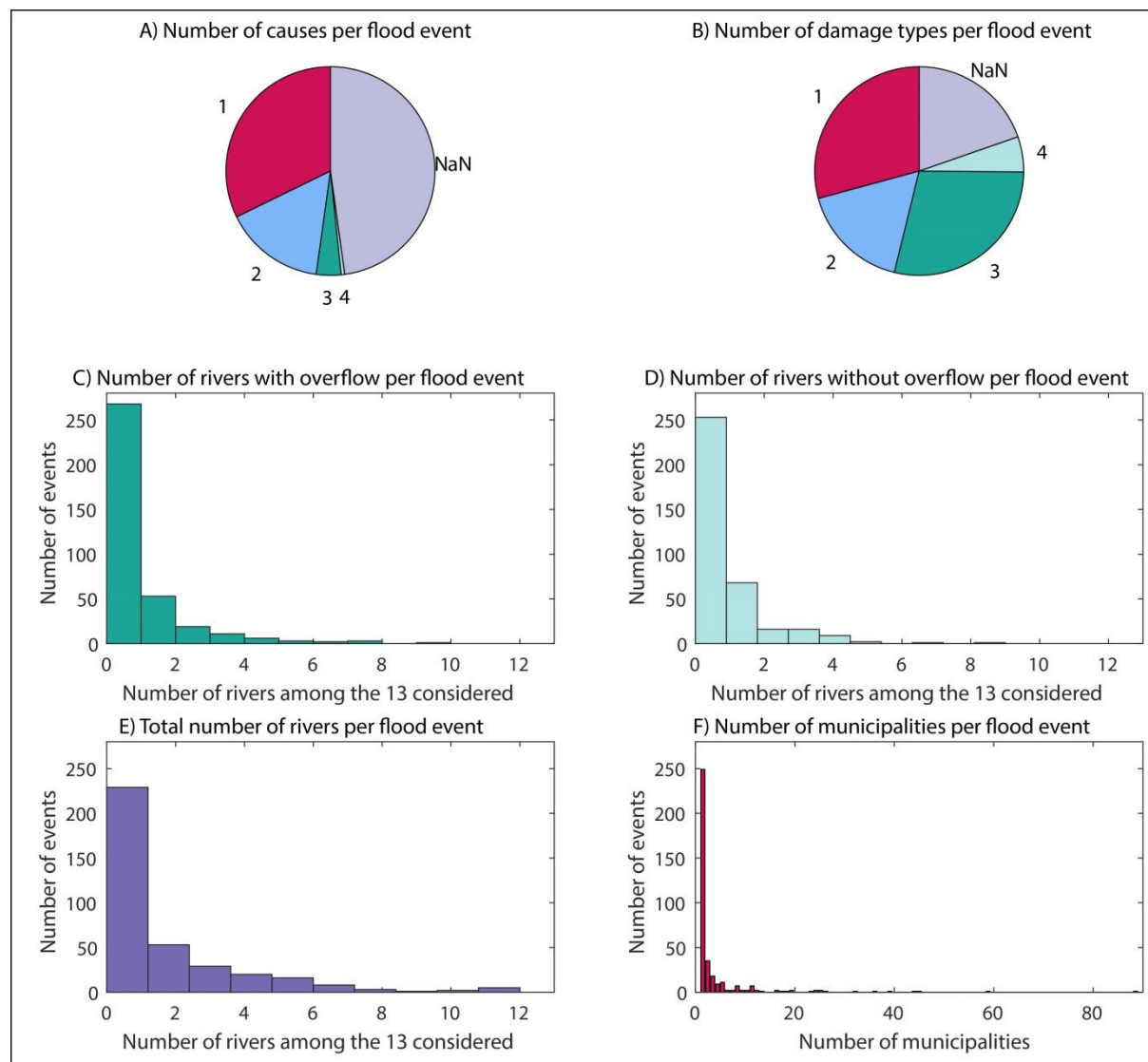
Figure 7: Characterization of the events' interranual distribution. A) number of documented causes; B) number of documented damage types; number of rivers per event among the 13 rivers studied C) with water overflow, D) without water overflow, E) with and without water overflow; F) number of impacted municipalities. For the latter, only the municipalities where water overflow has been reported are considered.
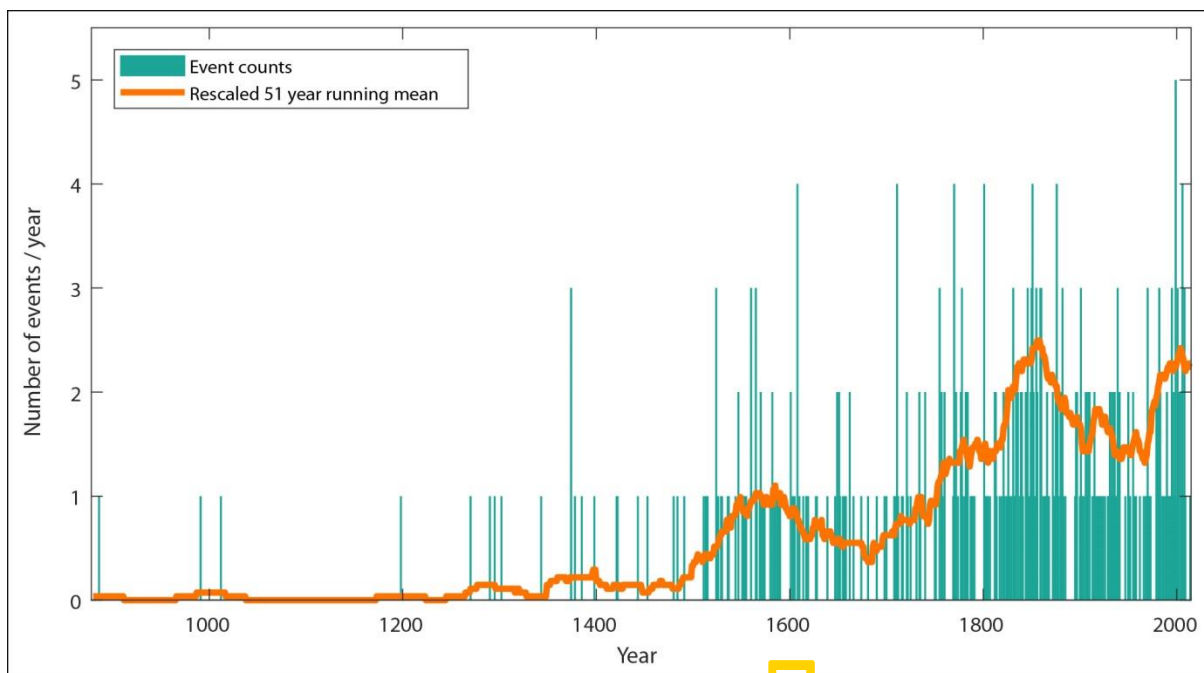
Figure 8: Chronology of all recorded events: annual distribution and smooth underlying trend.
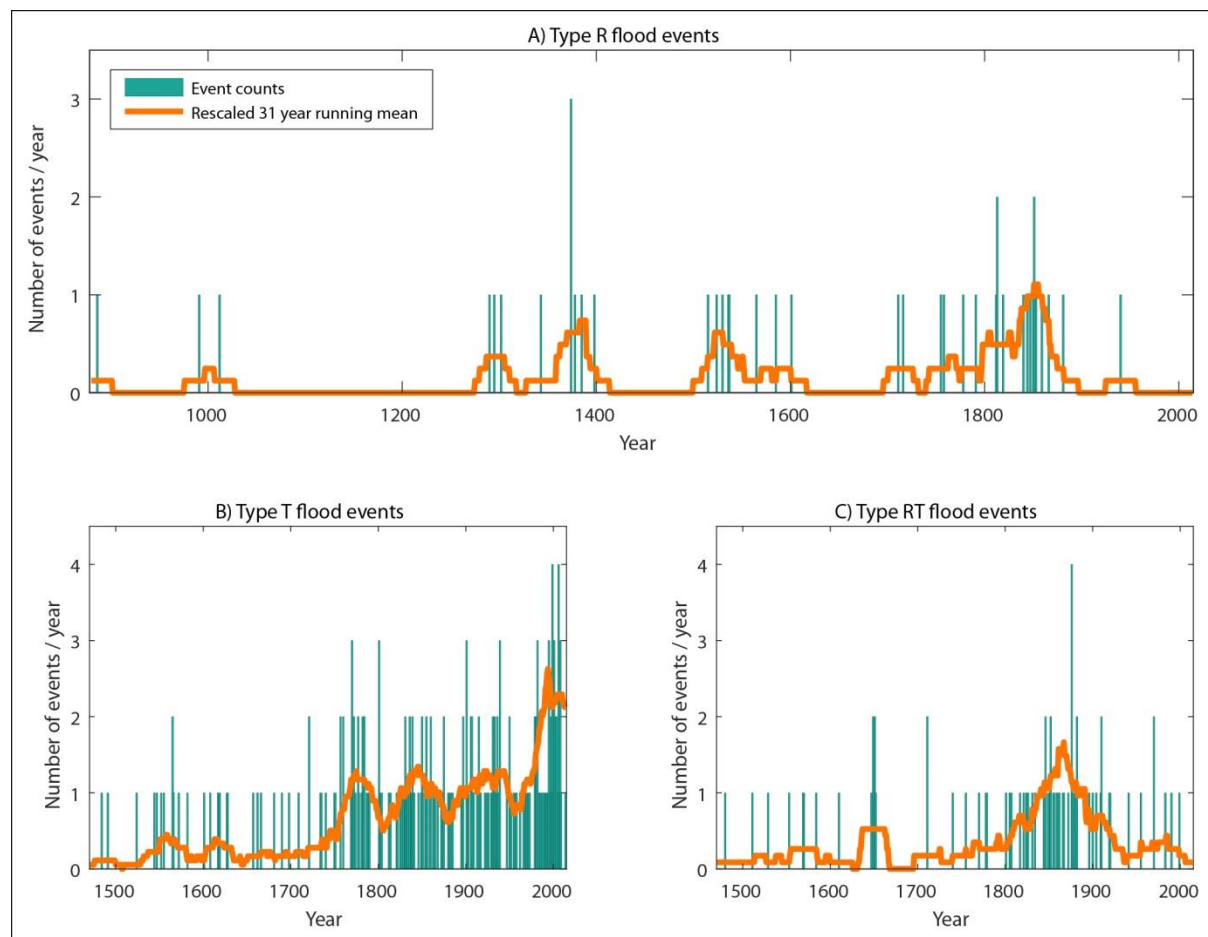
Figure 9: Chronologies according to events' hydrological configuration. Type R events correspond to flood events having affected the Rhine river alone. Type T events have affected one or several Alsatian tributaries of the Rhine river, but not the Rhine river. Type RT events have affected both the Rhine river and at least one of its Alsatian tributaries.
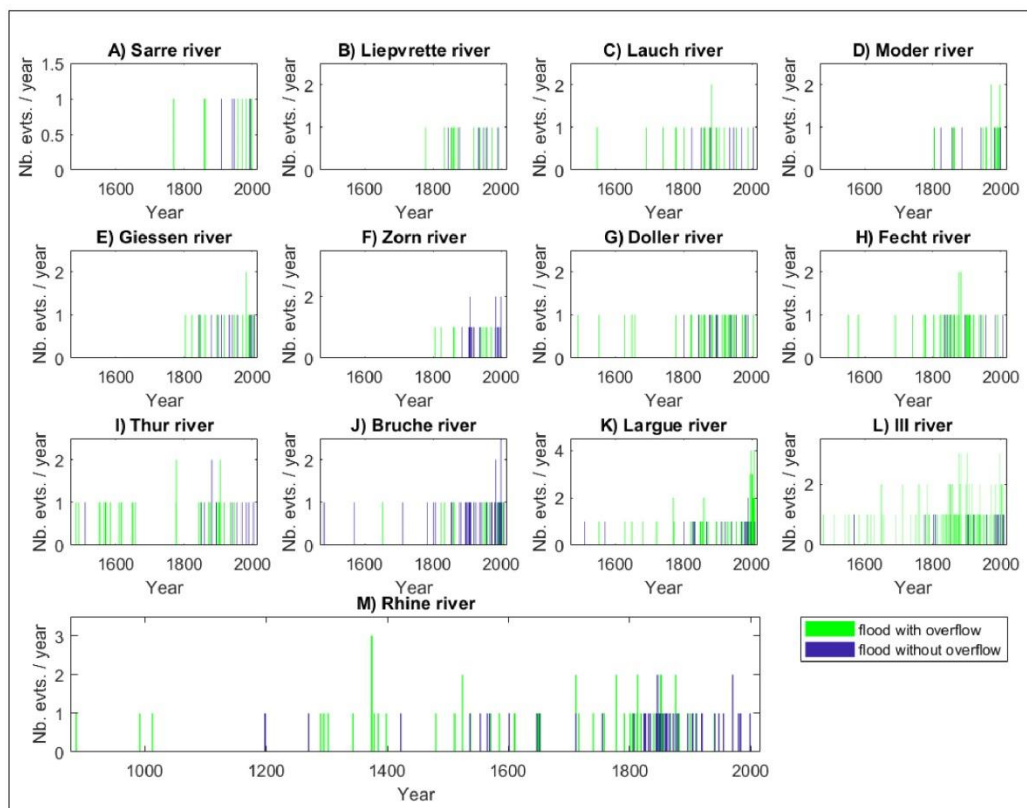
Figure 10: Individual chronologies for the 13 studied rivers: events with and without water overflow.
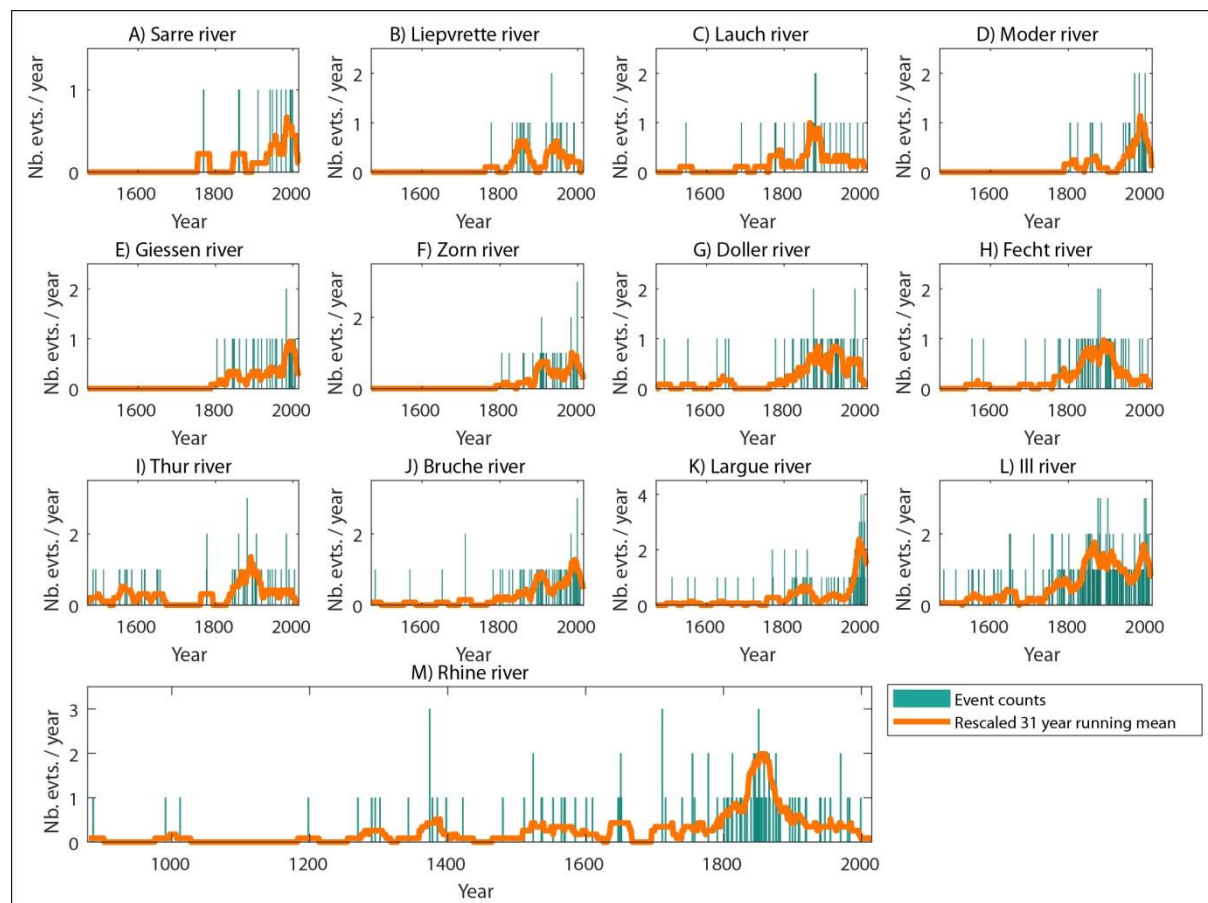
Figure 11: Individual chronologies for the 13 studied rivers: all events (with and without overflow) and underlying smooth trend.
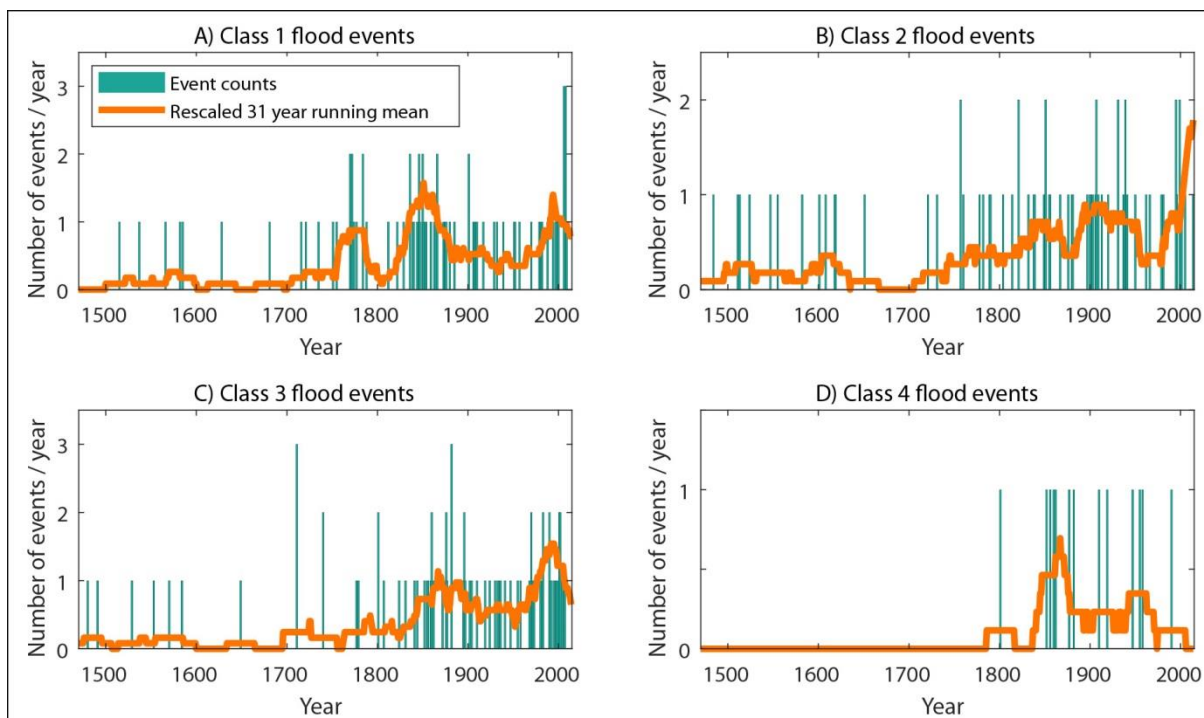
Figure 12: Chronologies according to the events' severity class as defined in Tables 1-2.
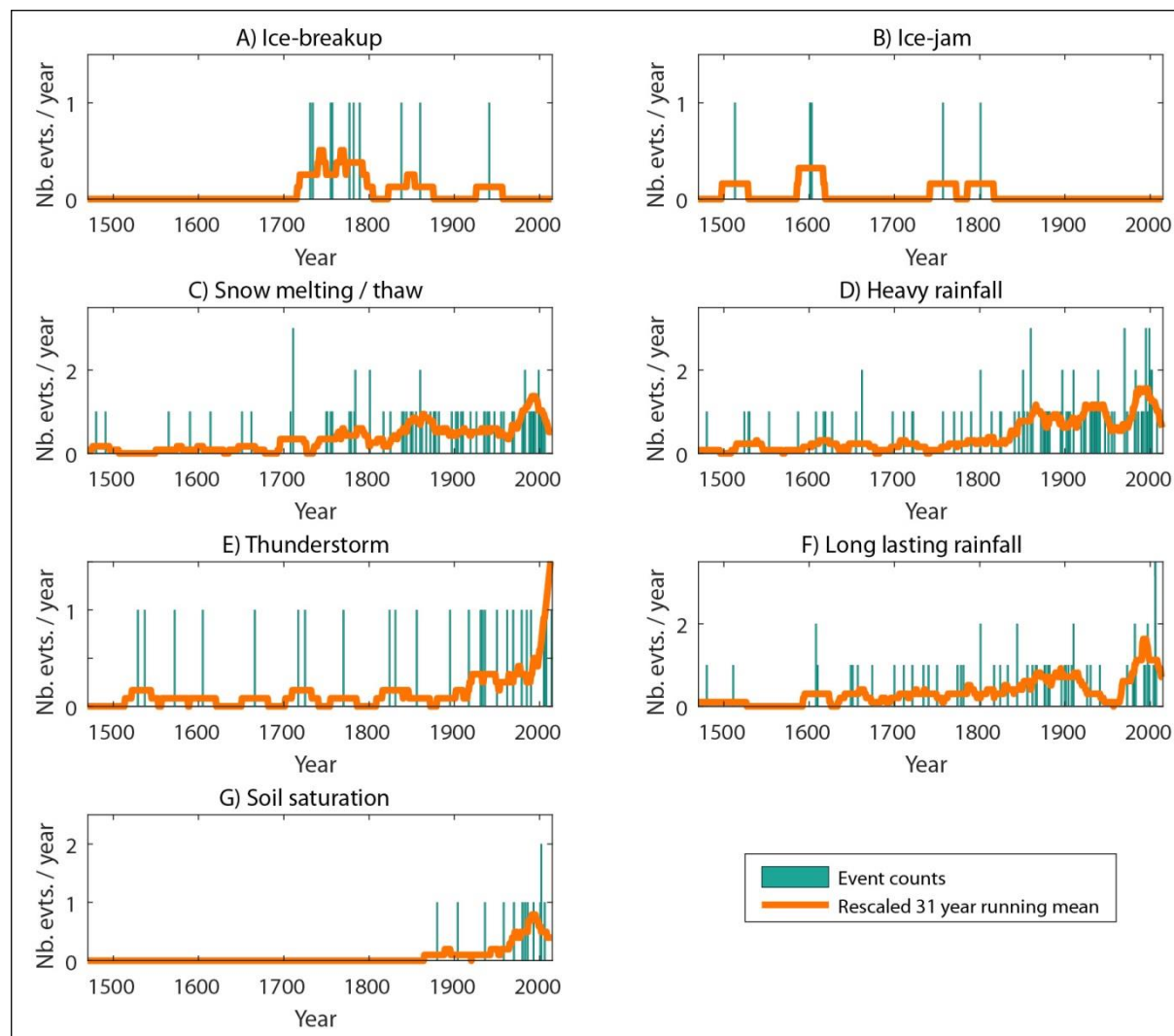
Figure 13: Chronologies of events according to their causes. Events for which several causes are documented (Figure 7A) appear in the different corresponding plots.
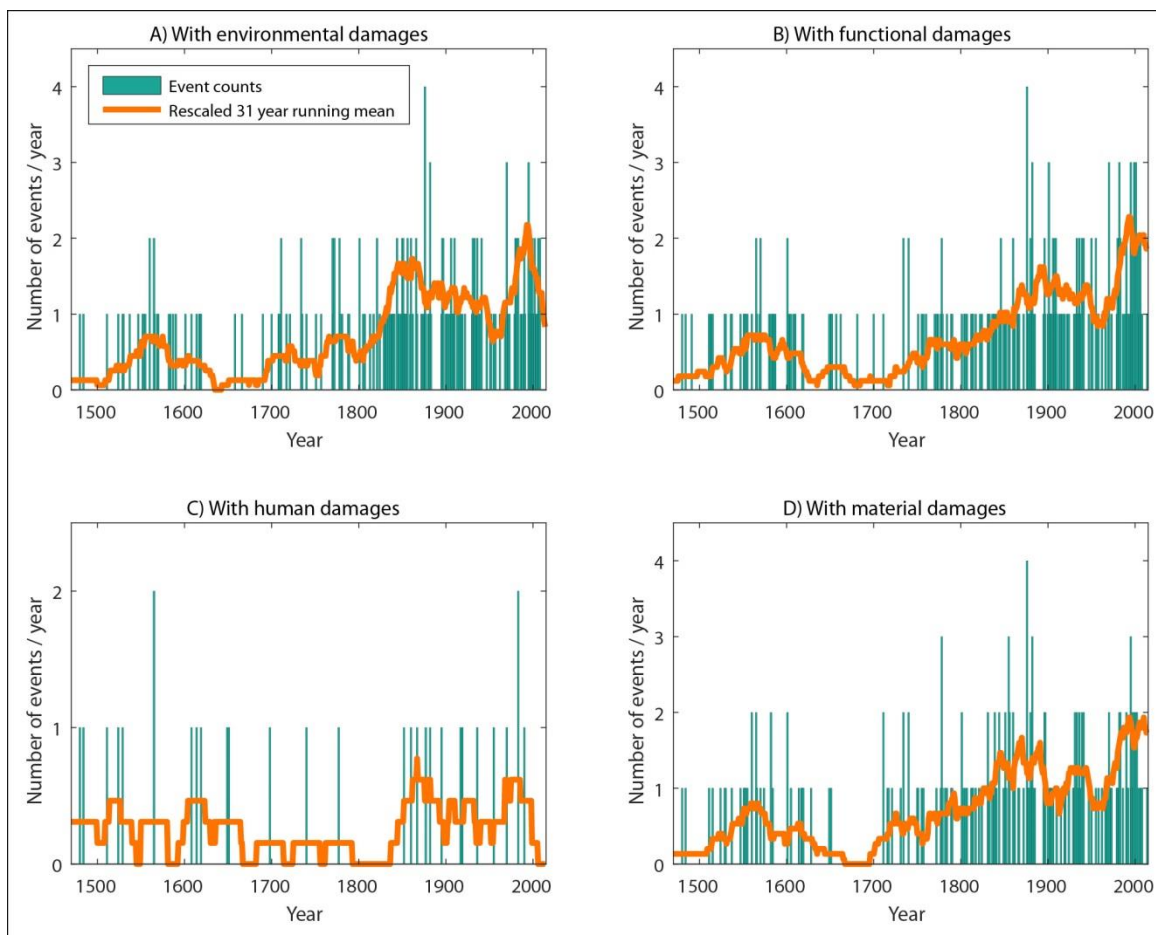
Figure 14: Chronologies of events according to their consequences (documented damage types). Human damages correspond to at least one people killed.
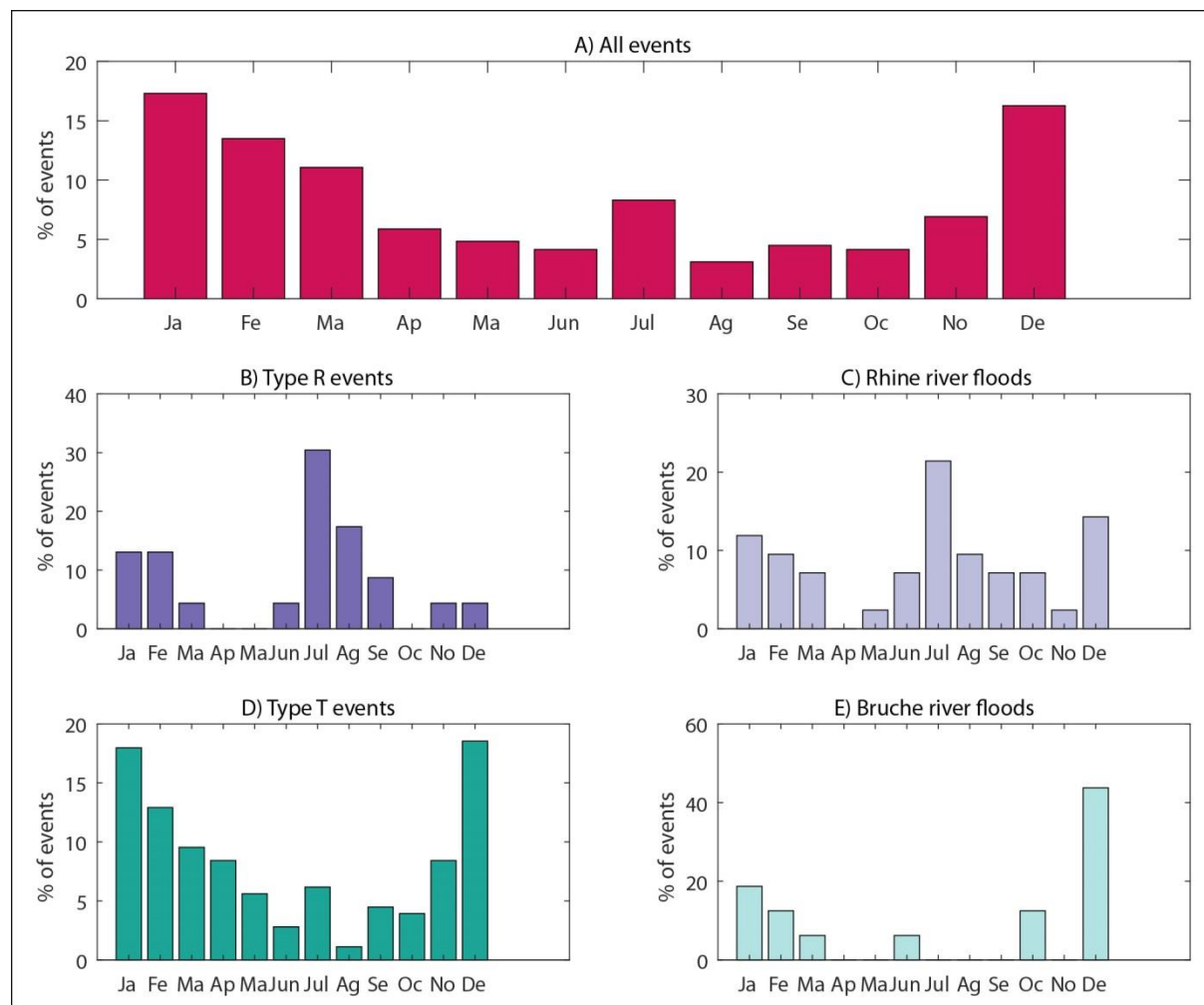
Figure 15: Flood events seasonality (monthly distribution). A) for all events; B-D) for the "Rhine river alone – R" and "Alsatian tributaries but not the Rhine – T" events; C-E) for all events with and without water overflow that have affected the Rhine and the Bruche rivers, respectively. For all (A) and Type R (C) – Type T (D) events, by definition, water overflow has been reported in at least one river.
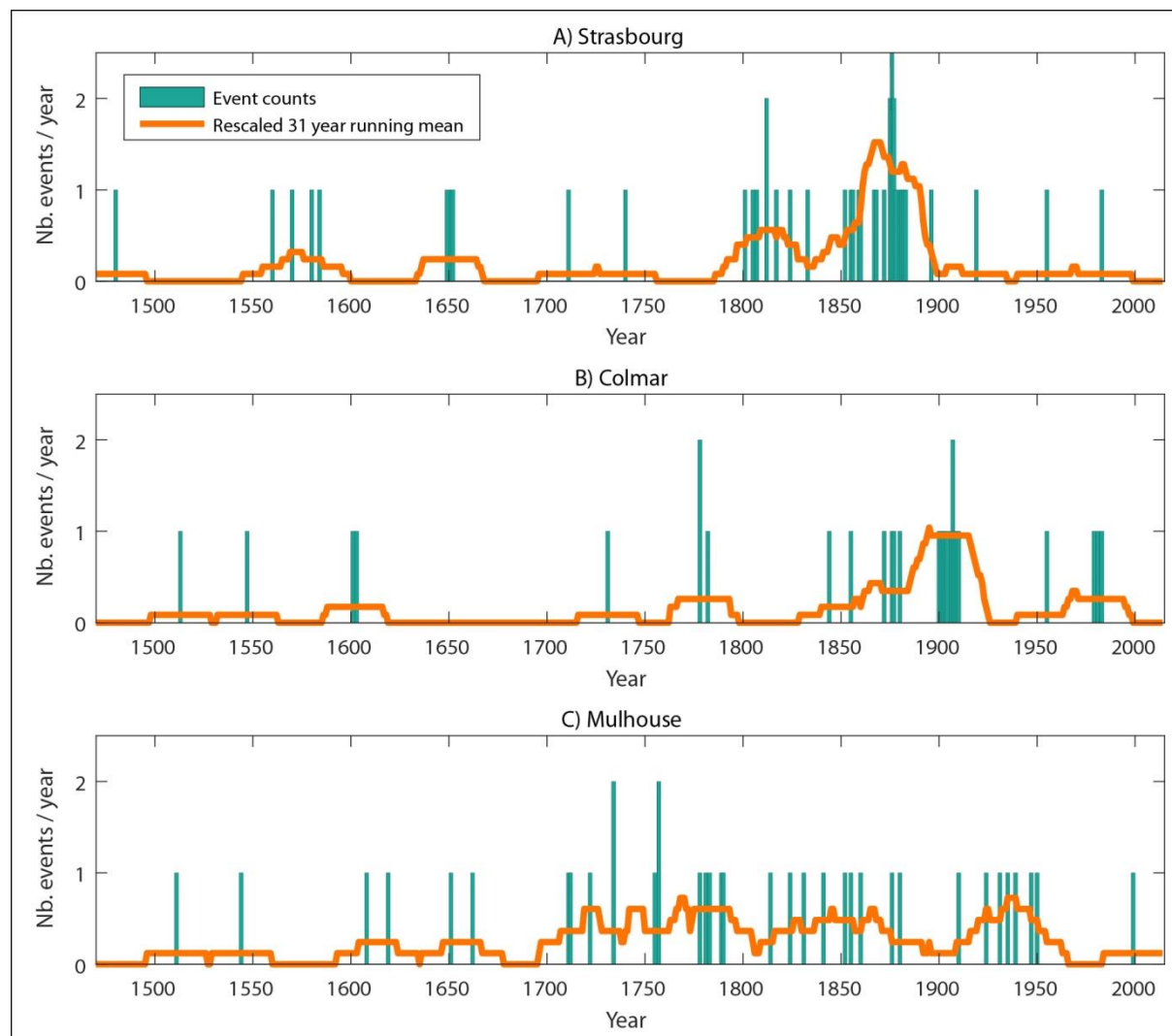
Figure 16: Chronologies for three specific municipalities.