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## Geo-historical analysis of flood impacts in Alpine catchments (HIFAVa database, Arve River, France, 1850–2015)

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1       Geo-historical analysis of flood impacts in Alpine catchments  
2               (HIFAVa database, Arve River, France, 1850 – 2015).

3  
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6  
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16  
17   **Abstract**

18   In France, flooding is the most common and damaging natural hazard. Due to global warming,  
19   it is expected to globally exacerbate, and it could be even more pronounced in the European  
20   Alps that warm at a rate twice as high in the Northern Hemisphere. The Alps are densely  
21   populated, increasing exposure and vulnerability to flood hazard. To approach long-term  
22   evolutions of past flood occurrence and related socio-economic impacts in relation to changes  
23   in the flood risk components (i.e. hazard, exposure and vulnerability), the study of historical  
24   records is highly relevant.

25   To this aim we analyze the newly constituted database of *Historical Impacts of Floods in the*  
26   *Arve Valley* (HIFAVa) located in French Northern Alps and starting in 1850. This database  
27   reports for the first-time flood occurrences and impacts in a well-documented Alpine catchment  
28   that encompasses both a hydrological and societal diversity.

29   We analyze past impacts in regard to their characteristics and evolution in both time and space.  
30   Our results show an increasing occurrence of impacts from 1920 onwards, which is more likely  
31   related to indirect source effect and/or increasing exposure of goods and people rather than  
32   hydrological changes. The analysis reveals that small mountain streams and particularly  
33   glacial streams caused more impacts (67%) than the main river. While increase in heavy  
34   rainfall and ice melt are expected to enhance flood hazard in small Alpine catchments, this  
35   finding calls to pay a particular attention to flood risk assessment and management in small  
36   catchments.

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39   **Keywords** : flood risk, exposure, vulnerability, history, socio-economic impacts, French Alps.  
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## 44 1. Introduction.

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46 On the mainland French territory flood is the most common and damaging natural  
47 hazard in terms of economic cost and number of municipalities concerned (Ministère de la  
48 Transition écologique, 2020). In highland regions, these events can be caused, among others,  
49 by summer thunderstorms, rain on thaw saturated soils, rain on snow or glacial lake outburst  
50 (Merz and Blöschl, 2003). The topography induces flood events with highly contrasted  
51 dynamics; from sudden events with large sediment transport in the upstream small catchments  
52 to multi-day events flooding large parts of the valley floor. This diversity of hydrological  
53 dynamics adds to the complexity in flood risk management. Furthermore, climate change is  
54 expected to increase extreme precipitation (Min et al., 2011) that could in turn increase flooding  
55 (Gobiet et al., 2014; Blöschl et al., 2020). This is especially the case for the European Alps  
56 where an increase in summer heavy rainfalls (Giorgi et al., 2016; Ménégoz et al., 2020) may  
57 threaten densely populated mountainous valley especially exposed and vulnerable to climate  
58 extremes (IPCC, 2019). With its long history of flooding, the densely populated Arve valley  
59 located in the Northern French Alps is indeed prone to experience the latter effects of global  
60 warming in the future.

61 Historical records constitute a source of reliable data to characterize past hydrological  
62 events because they contribute to give a comprehensive representation of these events and  
63 of their changes over long time scales in spite of the lack of instrumental data (Garnier and  
64 Desarthe, 2013; Barriendos et al., 2014; Wetter, 2017; Wilhelm et al., 2019). Impacts are  
65 considered as all types of outcomes for humans, society and ecosystems occurring in the  
66 aftermath of a physical phenomenon (IPCC, 2012).

67 The historical analysis of past events is useful for the study of catastrophe as we can  
68 hypothesize that these remarkable events are etched in the community's memory  
69 (Papagiannaki et al., 2013). Indeed, it is because these events have impacted the society that  
70 they are recorded in the historical records, i.e. have left a "social signature". Those high impact  
71 events can come close to the notion of a catastrophe as they can lead to a societal upheaval  
72 (Soanes and Stevenson, 2009) sometimes deleterious but also beneficial (behavioral change  
73 promoting prevention) (Garnier, 2017). High impact events are by nature rare, often resulting  
74 in a lack of available data (e.g. description of the event, time, extent, damages caused etc.).  
75 However, historical approach allows a social and spatio-temporal contextualization of the data  
76 (Giacona et al., 2017), making the reconstruction (date, impacts) of major flood events possible  
77 (Barriendos et al., 2003, 2019) and attesting the social apprehension of the phenomenon (Gil-  
78 Guirado et al., 2016).

79 Numerous historical databases were built to document past flood occurrence and  
80 magnitude, such as the Prediflood database (Barriendos et al., 2014), and some, as the  
81 database from Thoumas (2019), allow to analyze the climatic fluctuations. In contrast to these  
82 latter databases focusing on hydrological events, some databases collected the  
83 socioeconomic impacts of floods such as the APAT database (Lastoria et al., 2006), the press  
84 database on natural hazards and climate change from Llasat et al. (2009), the database of  
85 high-impact weather events in Greece from Papagiannaki et al. (2013), the EUFF database  
86 (Petrucci et al., 2019) and the SMC-Flood database (Gil-Guirado et al., 2019). Some  
87 databases stand out as the participative flood database ORRION (Giacona et al., 2019) or the  
88 database built by the RISC-KIT project (Garnier et al., 2018) which aim to develop methods  
89 and management tools and discuss the trajectories of vulnerability.

90 Floods, as natural hazards, are physical phenomena naturally occurring and can, when  
91 certain conditions are met, cause harm to societies. They can be interpreted as a social  
92 construction (Beck, 1992) since exposure of human activities and social vulnerability play a  
93 large role in the severity of the impacts. Flood impacts databases, constituted from historical  
94 records, can be considered as the expression of society's concerns, risk perceptions (fear,



95 habit) and values (based on reported impacts). The recording of flood impacts, or the failure  
96 to record them, provides a subjective measure of the events that were considered worth  
97 reporting for various reasons across historical periods. Flood impacts result from the  
98 interaction between the natural phenomenon and the dynamics of exposure and vulnerability.  
99 As vulnerability we understand the inclination to damage of various exposed goods, activities  
100 or people constituting a given territory (Leone and Vinet, 2006). We consider the vulnerability  
101 as a dynamic system articulated to numerous physical and societal factors (Antoine, 2011).  
102 This system can evolve in time and space (Cutter, 2003). Major natural disasters, such as  
103 floods, are often displayed as unforeseeable events whereas the historical facts give evidence  
104 of the contrary (Garnier, 2016, 2019). Yet the society's vulnerability may increase as the past  
105 disasters are forgotten, leading to a "society of risk" (Garnier, 2019). Historical approach allows  
106 to explore the trajectories of hazard and vulnerability in response to changes in climate, land  
107 use and flood risk management (Gil-Guirado et al., 2016).

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109 The present paper introduces a newly constituted database of flood impacts of the Arve  
110 River and its tributaries (Northern French Alps). The database called "*Historical Impacts of*  
111 *Floods in the Arve Valley*" (HIFAVa) covers all impacts caused by hydrological events that  
112 occurred since 1850.

113 The study of this database, the first one documenting a mountainous catchment, ultimately  
114 aims at analyzing the interactions between social and natural dynamics engendering flood  
115 impacts. In this paper we analyse the impacts with respect to their nature and evolution in both  
116 time and space.

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## 119 2. Study area: the Arve River.

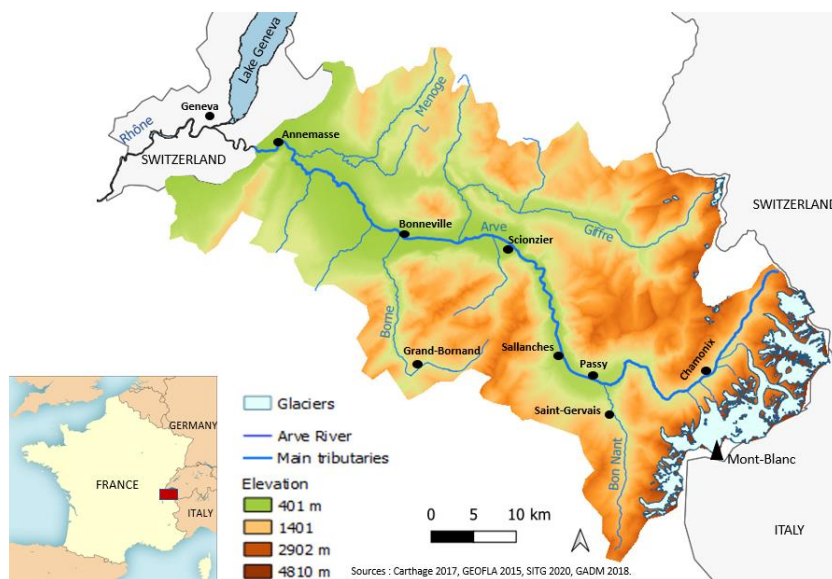
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### 121 2.1. Description of the physical setting of the Arve River.

122 The Arve River is located in the Northern French Alps (Figure 1), flowing from the high  
123 elevations of the Mont-Blanc summit (4810m a.s.l.) to the Swiss lowlands (330m a.s.l.), where  
124 it flows into the Rhône River. The surface area of its catchment is 2164 km<sup>2</sup> with the largest  
125 part higher than 1000m a.s.l.. The main tributaries of the Arve River are the Giffre, the Borne,  
126 the Menoge and the Foron Rivers. Since 1850, i.e. the start date of the studied period, the  
127 Arve River is already almost completely embanked (Mougin, 1914; Gex, 1924; Peiry and  
128 Bravard, 1989).

129 Due to large difference of altitude between high and lowlands, the Arve flows can be defined  
130 by two hydrological regimes following an upstream to downstream continuum:

- 131 - The upstream part of the catchment (down to the city of Sallanches; Figure 1), has a  
132 glacio-nival regime due to the numerous glacial tributaries flowing from the Mont Blanc  
133 massif (Viani et al., 2018). Low flows occur in winter and early spring (December to  
134 March) and the high flows in summer (maximum in July and August) because of the  
135 strong contribution of ice melting (Bernard, 1900). Floods mainly occur in summer due  
136 to the synchronicity of both ice melt and intense subdaily rain storms. In this part of the  
137 catchment, the flood plain is narrow and the slope inclination is high.
- 138 - At lower elevations (i.e. downstream Sallanches) the regime becomes more and more  
139 nival downward. Low waters mainly occur in winter and reach the highest levels  
140 between late spring and early summer with the snowmelt. Between Sallanches and  
141 Bonneville, floods mainly occur in summer and autumn due to the conjunction of  
142 intense daily rain storm, snow melt and, in a lesser extent, ice melt contribution.  
143 Downstream Bonneville, floods occur at any time of the year due to even more various  
144 hydro-meteorological interplays. The valley floor is here wide and may be affected by  
145 extended flooding.



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Figure 1. The Arve catchment with its location in the Northern French Alps, its topography, its main hydrological network and the main cities.

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## 2.2. Socioeconomic setting and land use.

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There are 106 municipalities located in the Arve catchment, globally facing a major population growth since 1850. For instance, the population has been multiplied by a factor of three in about 170 years at Chamonix (2 304 to 8 611 inhabitants between 1848 and 2016) and by a factor of thirty-four in Annemasse (1 047 to 35 712 inhabitants between 1848 and 2017) (INSEE, 2019). These numbers also hide large seasonal variations related to tourism activities. This is particularly the case in Chamonix where the number of residents increases up to ten times in high season. Most inhabitants live in the valley floor and the foothills that also welcome most of the farming, industrial and tourism activities as well as the main transportation routes and urban areas. Since 1965 and the opening of the Mont-Blanc Tunnel Highway the Arve valley is a major trans-Alpine route connecting France and Italy.

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The socioeconomic setting of the valley follows an upstream-downstream distribution pattern. The period from 1850 to 1913 experienced a great touristic development (thermal bath of Saint-Gervais and mountaineering in Chamonix). The economy around Chamonix is essentially based on mountain tourism. In 1921, 250000 tourists were visiting Chamonix each year (Gex, 1924). In 2015 the lodging capacity in the valley reached around 416400 equivalent touristic beds. This part of the valley has undergone a rapid urbanization. In 1804, the discovery and exploitation of spring water for hydrotherapy in Saint-Gervais (Gex, 1924) fostered the construction of touristic accommodations. Around Bonneville, the valley is a densely populated corridor characterized by an old bar turning industry, born from the watch manufacture and nearby hydropower resources. The small valleys of the Arve tributaries are sparsely populated and the economy is based on tourism and farming. Due to the attractiveness of the city of Geneva, the valley from Bonneville to the Rhône River confluence is characterized from the 1960's by a major population growth, extended industrial areas and strong urbanization. Between the town of Cluses and Geneva the valley floor is almost continuously built-up.

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### 3. Material and methods of the HIFAVa database.

#### 3.1. Collecting data from historical archives.

A first historical study has been carried out to draw a flood chronicle of the Arve valley between the 18<sup>th</sup> and the 21<sup>th</sup> century, with a particular focus on the hydro-meteorological circumstances of the flood events (Mélo et al., 2015). As sources are more abundant over the last 165 years (1850-2015), this period was defined as the studied time frame of the HIFAVa database. Only events mentioned in at least two sources were integrated in the database. Since 2015, data have been further collected to complete the preliminary dataset from Mélo et al. (2015).

Information on floods and related impacts has been collected from various sources. Primary sources range from handwritten archives like municipal acts to departmental archives (e.g. reports of the *Préfecture* and of town councils). Secondary and tertiary sources are respectively made of published documents (newspapers, reports, books) and pre-existing databases. The database of historical records providing a chronological and synthetic layout of the data is composed of (Table A1):

##### Manuscript materials:

- Most of the manuscripts are kept in the departemental archives (*Archives Départementales de Haute-Savoie*: ADHS) (Conseil départemental de la Haute-Savoie, n.d.) or in the municipal archives (*Archives municipales*: AM) of the towns of Chamonix, Cluses and Bonneville. The departmental and municipal archives also contain records older than the Savoy annexation by France in 1860. The records can be private or from a public institution.

##### Printed materials:

- Articles of scientific journal and books used in this study have been published since 1914. They mostly correspond to analyses of the regional hydrology (Mougin, 1914; Rousset-Mestrallet, 1986) but they can also focus on single hydrological events (Pardé 1931; Rougier 2002; Goy 2002) and risk assessment (Douvinet et al., 2011).
- Open-access online municipal risk prevention plans (*Plan de Prévention des Risques*: PPR; and *Plan de Prévention du Risque Inondation*: PPRi) (Préfecture de la Haute-Savoie, n.d.) as preventive regulatory documents used to delineate risk areas, often compile historical flood events that affected municipalities.

##### Newspapers:

- Most of the newspapers used are regional, but one is published at national level (*Le Figaro*) and another is printed in Geneva, Switzerland (*Le Journal de Genève*). Most of the newspapers can be found online or are kept in the departmental or municipal archives. Newspapers describe the causes and consequences of the event and sometimes provide instrumental data and illustrations. They also inform about the public authority response and the past ongoing discussion.

##### Other records:

- The national database of historical flooding (*Base de Données Historiques sur les Inondations*: BDHI) that gathers floods events considered as “remarkable” in the French territory (Ministère de la Transition Ecologique, n.d.; Boudou, 2015) has been used.
- The database created by the department of Restoration of Mountainous Areas (*Restauration des Terrains en Montagne*: RTM) from the public institution managing the French public forests (*Office National des Forêts*: ONF). The ONF-RTM database gathers transcriptions of observations of the RTM officials as well as information collected from diverse primary sources. These data (labelled RTM in the HIFAVa



228 database) are freely available through the open-access and online ONF-RTM database  
229 (RTM and ONF, 2012). Some specific ONF-RTM reports are also included in the  
230 HIFAVa. The RTM database was built to assist the management of small tributaries.  
231 - A movie realized in 1990 by the RTM is also mentioned as a source.  
232 - Some records are from the *Syndicat Mixte d'Aménagement de l'Arve et de ses*  
233 *Affluents* (SM3A), which is the institution in charge of the management of the Arve River  
234 and its tributaries since 1994.

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### 3.2. Characteristics of the HIFAVa database.

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### 3.3. Text mining.

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The flood impacts of the HIFAVa were categorized through a text quantitative content analysis with the KH Coder software (Higuchi, 2015). The description of the impacts comes from comments contained in the records. The most frequent words have been gathered in order to determine representative categories of the database content. A category is made of several words assigned to a coding rule. Categories have been inspired by the flash flood impact severity scale of Diakakis (2020). This analysis has led to the following seven categories with example of the assigned words:

- Transport network: e.g. "road", "bridge", "railway", "street".
- Urbanized areas and residential buildings: e.g. "house", "town", "basement".
- Natural environment: e.g. "forest", "field", "yield", "sediment transport".
- Protection infrastructures and dams: "dikes" and "dam".
- Industrial, commercial and recreational facilities: e.g. "mill", "factories", "golf", "camping", "hotel", "school".
- Critical installations: "drain", "power transformer".
- Victims: "dead", "injured", "missing", "evacuee".



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A more in-depth analysis will be conducted later on to define severity classes based on the nature of the impacts. This future analysis will be based on the work of Barriendos et al., (2003), Llasat et al (2005, 2013) and Boudou et al. (2015).

ID	Event	Sources	Start_day	Start_month	Start_year
140	58	Payot 1951 / Goy 2002 / RTM / BDHI	12	7	1892
670	263	RTM / Dauphiné libéré : 26/07/1996, 27/07/1996, 30/07/1996 and 02/08/1996	24	7	1996

Start_date	Time_unc	Hour	River	Impacts	Municipality
12/07/1892	D		Bon Nant	Thermal Bath, victims	Saint-Gervais-les-Bains
24/07/1996	H	11 pm	Arve	City center	Chamonix-Mont-Blanc

Impact_latitude	Impact_longitude	Space_unc	Count	Hydrometeo_descript	Water_level
45.8965	6.70596	A	175	No entry	
45.9257	6.87057	A	0	No entry	0,4m

Flood_description	Impacts_decription
Debris flow. 30 minutes to flow from the Tête Rousse glacier to the Arve confluence.	More than 175 victims, destruction of most of Thermal Bath, mud over the first floor.
Debris flow, logjam under bridges.	Numerous houses and the city center are under water. Fuel oil pollution due to basement flooding.

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Table 1. Extract of the HIFAVa database showing its structure. Refer to the Online Resource 2 for details about the column contents.

## 4. Results and discussion.

### 4.1. Evolving sources over time.

During the studied period, the diversity and the quantity of sources in which mentions of impacts have been found fluctuate (Figure 2). Among the existing databases used, the BDHI database for instance continuously covers the studied period but was sporadically informative since it only contains two mentions of flood impacts in the Arve catchment, respectively in 1892 and in 1987. By contrast, the SM3A database appears later (1979) in the studied time frame.



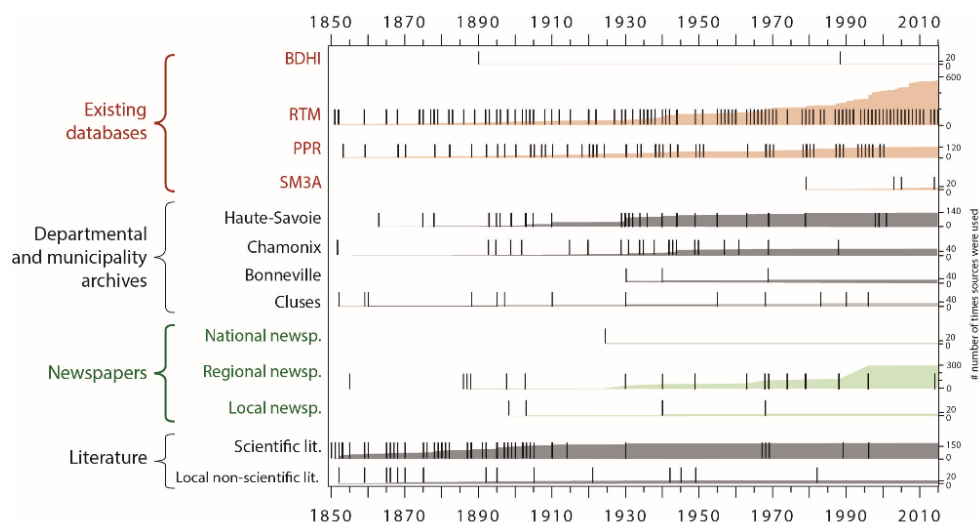


Figure 2. Number and diversity of studied sources to document flood impacts.

RTM (38% of the sources), regional newspapers (20%) and scientific literature (13%) constitute the main sources of information on past flood impacts throughout the studied time period. Sources from the literature are particularly useful (54%) to document the period between 1850 and 1910. Then, materials from the departmental and municipality archives are abundant between 1900 and 1970, especially those from Haute-Savoie (20% of the total registered sources for this period) and Chamonix (7%). Between 1940 to 2015, the RTM represents 58% of the sources describing the impacts.

One of the evolutions of the sources is the increase in the newspaper articles mentioning flood impacts. Following the 1881 press freedom French law, the 1880-1889 decade marks the emergence of articles recording natural hazards, such as flood impacts (Ferenczi, 1996). However, the 1855 flood in Bonneville was already reported by the swiss newspaper, *Le Journal de Genève*.

Although a few sources (e.g. the municipal archives of Sallanches) remain to be examined, most of them have been analyzed in order to constitute the database. Hence, we consider that we have a comprehensive view of past flood impacts since 1850 over the whole Arve catchment.

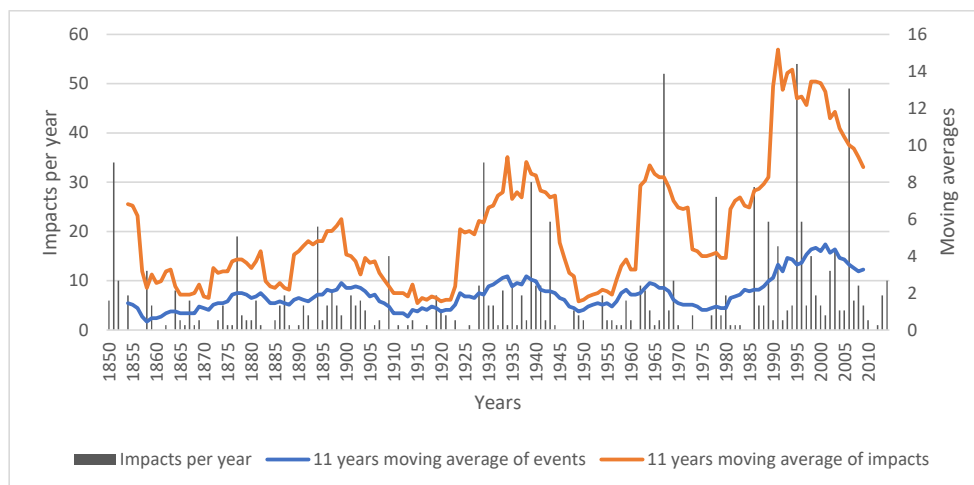
#### 4.2. Changes in impacts over time and space.

From 1850 to 1920, the number of impacts fluctuates and only four years are remarkable with more than 15 impacts (1852, 1878, 1895 and 1910). From 1920, years with such a large number of impacts become more frequent (1930, 1940, 1944, 1968, 1979, 1987, 1990, 1996, 1997 and 2007) and the total amount of impacts per year reaches 54 in 1996 (Figure 3). The decennial moving average of the impacts' number highlights an overall increase over the 165 years, punctuated by periods with less frequent impacts (in 1910-1923, 1950-1960 and 1975-1980).

Besides, the number of recorded flood events stays relatively stable between 1.5 and 3 events per year on average until 1990, then it rises up to 4.5 events per year. Therefore, the overall increase in recorded impacts seems partly disconnected to changes in flood occurrence. Only the latest period (1990-2015) of increasing impacts may be partially due to a rise in flood occurrence. In particular, the increase in flood impacts starting in the 1920's and well-marked



332 since the 1960's, especially by repeated years with very high numbers of impacts, may be  
333 explained by other processes as discussed in the next section.  
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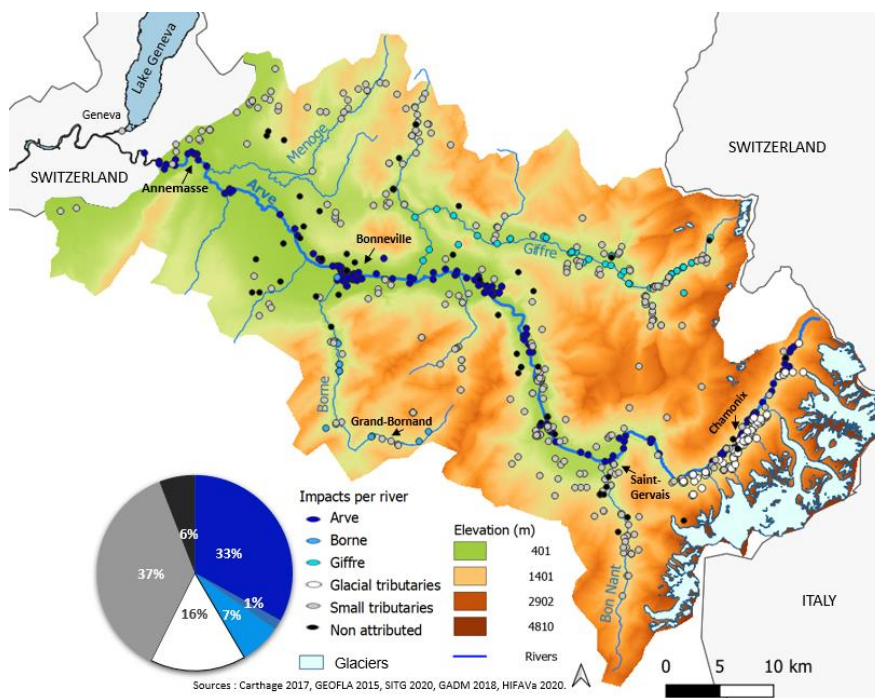


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336 **Figure 3. Occurrence of impacts and moving averages of impacts and associated flood events.**  
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338 When analyzing the spatial distribution of the flood impacts, we can see that they are  
339 spread over the entire catchment (Figure 4). They are, however, mainly gathered in the Arve  
340 valley around Chamonix and Bonneville (24 and 12,5% of total impacts recorded in the Arve  
341 catchment). These high numbers may be due to the fact that these towns are both among the  
342 most densely populated and the closest towns to the Arve River. The impacts caused by the  
343 Arve River floods represent 33% of all recorded impacts, and its two main tributaries, the Giffre  
344 and the Borne Rivers, have only caused 8% of the recorded impacts. In fact, most impacts are  
345 due to small torrential streams (53%). Among them, almost a third is related to glacial  
346 tributaries, while these tributaries are localized only in the uppermost part of the catchment  
347 near Chamonix. For instance, small torrential tributaries such as the Arveyron, the Grépon (left  
348 bank tributary close to Chamonix) or the Bon Nant have caused alone more impacts than the  
349 Borne River itself.



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352 Figure 4. Location and distribution of flood impacts caused by the Arve and its tributaries. The  
353 category “non attributed” corresponds to the part of impacts for which it was not possible to  
354 attribute a river, either because events are related to overland flows or because of the location  
355 between two or more rivers.

356

357 The Arve tributaries produced disasters characterized by numerous and major flood damage.  
358 Among them, the 1987 Borne River flooding in its uppermost part washed away the municipal  
359 campsite of the village of the Grand-Bornand causing 23 casualties and heavy economic  
360 losses (Meunier, 1990). In addition, the 1892 glacial lake outburst from the Tête Rousse glacier  
361 in the Bon Nant River (which literally translated means “Good Stream”) swept away the thermal  
362 bath of Saint-Gervais (Figure A1) and 33 houses causing at least 175 casualties. The glacier  
363 was drained in 2010 and is today closely monitored to avoid such a brutal and disastrous  
364 natural event (Garambois et al., 2016).

365 All these high impacts events are due to sudden, highly-dynamic summer floods of tributaries,  
366 often aggravated by large sediment transport. Some towns located along the Arve River – such  
367 as Sallanches – are more prone to tributary’s floods because embankments have been built  
368 and efficiently prevent impacts from the Arve flooding. In contrast, there are very few impacts  
369 recorded in high altitude, probably due to the sparse human settlements.

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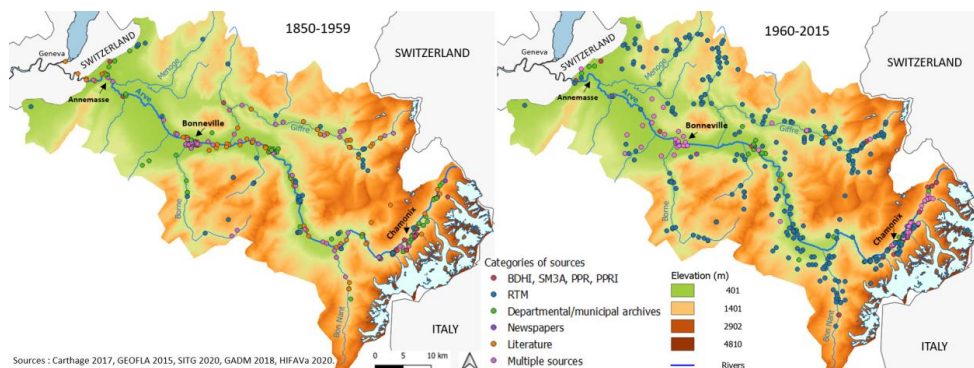
### 371 4.3. Potential drivers of changes in the number and spatial distribution 372 of impacts.

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374 The increase in the number of impacts starting in the 1920’s and well-marked from the  
375 1960’s can be explained by multiple factors such as indirect source effect, increasing flood  
376 activity and/or increasing exposure of goods and people. However, the flood occurrence did  
377 not change significantly before the 1990’s (Figure 3). Therefore, the increase in impacts cannot  
be explained by changes in flood occurrence, at least prior to 1990.



378 To decipher the potential source effect in the increase in impacts since 1960, maps of  
379 the impacts by sources have been drawn for the periods before and after 1960 (Figure 5). For  
380 the first period (1850-1959), three main sources describe 64% of the impacts (literary records  
381 28%, RTM 18% and departmental and municipal archives 18%) and for 29% the information  
382 comes from more than one source. The impacts are mainly gathered along the Arve and the  
383 Giffre Rivers, especially in the valley of Chamonix and between the towns of Cluses and  
384 Bonneville.  
385 For the second period (1960-2015), the RTM reports 65% of the impacts, and 20% come from  
386 multiple sources while departmental and municipal archives and the PPR/PPRI describe 5%  
387 each. Information coming only from literature decreases substantially (122 described impacts  
388 in the first period to 3 impacts in the second), SM3A records start in 1979 and only document  
389 the Giffre and the Bon Nant Rivers. The distribution of the impacts is much more scattered  
390 across the whole catchment than during the first period. The impacts are not anymore gathered  
391 along the Arve River, since most of them result from small tributaries. Impacts described by  
392 more than one source are located in the valley of Chamonix and around Bonneville, probably  
393 because these economic and touristic centers arouse interest of many sources (newspapers,  
394 departmental and municipal archives and RTM). The touristic specificity of valley and its  
395 international stature can explain the media coverage. We can assume that, floods are more  
396 likely to be reported in newspapers as when they happen in a location known by the reader. In  
397 addition, the strong emergence of the RTM since 1940 (Figure 2) can explain the rise in  
398 impacts caused by small tributaries illustrates by the Figure 5. Following the floods of the  
399 Rhône, the Loire and the Garonne in 1854, the 1858 law against urban flooding places flood  
400 control at the heart of the national legislation for the first time. In the following, the RTM  
401 department was formed for the reforestation of mountains slope in order to prevent the  
402 reproduction of major floods. The department became quickly efficient and since 1860  
403 collected numerous reports. Built for the study and management of small tributaries, the RTM  
404 database became the main source of information since 1930 for the HIFAVa database.  
405



406 Sources : Carthage 2017, GEOFLA 2015, SITG 2020, GADM 2018, HIFAVa 2020  
407 Figure 5. Distribution of the sources describing the recorded flood impacts in the Ave  
408 catchment during two periods: 1850-1959 and 1960-2015.  
409

410 The rise in the number of impacts per flood may be partly explained by the fact that distinct  
411 impact types in the same location were reported and therefore referenced under distinct impact  
412 ID while they were not differentiated in previous periods. Recent sources seem to provide more  
413 accurate information on the impacts and their locations. In older sources, impacts are most of  
414 the time documented at the city scale (21% of the impacts for the first period, and 10% for the  
415 second period). Thereby, all these impacts are stored in the database in a single line with an  
416 uncertainty code for the impact location corresponding to the municipal level. In most recent

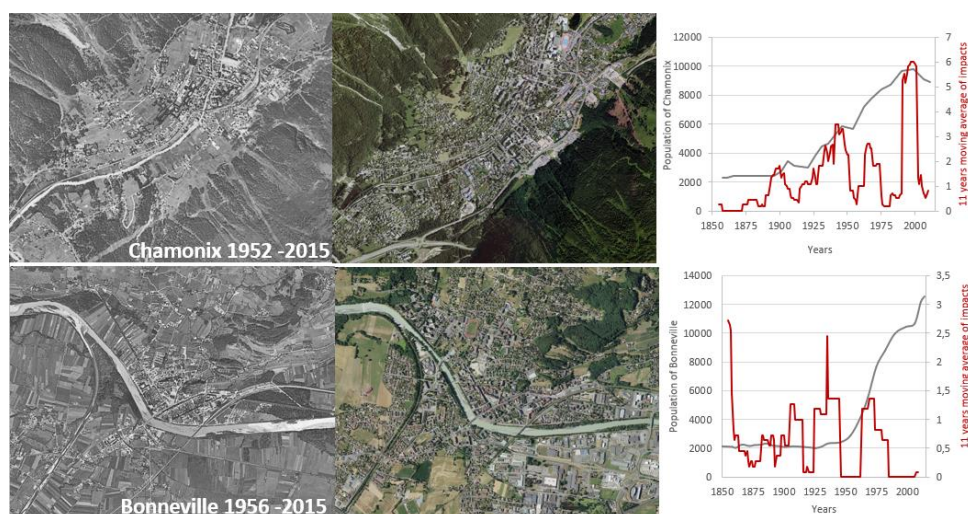


417 sources, impacts' locations are described more accurately allowing to record them at a  
418 resolution up to the building scale. As a result, impacts are stored in as many lines as impacts  
419 locations can be identified, with an uncertainty code for the impact's location corresponding to  
420 the building or neighborhood level (85% of the impacts for the second period). For example, in  
421 1996 fifty-three impacts were recorded for a same event and fifty of them were located in  
422 distinct places in Chamonix. The rise in impacts can also be due to numerous impacts in  
423 different locations, as the flood of 1990 which impacted six towns in two different sub-  
424 catchments (the Arve and the Giffre catchments). However, in order to overcome the bias  
425 induced by the recording of impacts according to their location, we have aggregated the  
426 impacts at the municipality level. That is to say, all the impacts reported for a given municipality  
427 that were caused by the same event (thus the same day) are recorded under the same line in  
428 the database. This results in 562 "aggregated" impacts instead of 917 impacts initially. From  
429 these data, we have redrawn Figure 3 (Figure A2) comparing the moving average of impacts  
430 and associated events. We can see that the trends are significantly the same. There is an  
431 increase of impacts (here starting soon as 1890s) and a late increase of events (1990s). Thus,  
432 the way the impacts are stored in the database (by location or by municipality) does not affect  
433 the observed temporal changes in impacts.

434

435 Changes in exposure and vulnerability related to land use is another potential  
436 explanation of the rise in the number of impacts (Magnan et al., 2012; Garnier and Desarthe,  
437 2013; Camuffo et al., 2020). A major population growth happened, especially in Bonneville and  
438 Chamonix, leading to a strong and fast urban sprawl in the flood plain between the 1950's and  
439 the 2010's as shown by aerial photographs (Figure 6). They also show the vanishing of the  
440 alluvial forest (Dufour and Piégay, 2006) and cultivated fields to the benefit of urbanization in  
441 both towns. The population growth in the Arve Valley varies according to the towns. Upstream,  
442 in Chamonix, the demographic expansion dates back to the early 20<sup>th</sup> century with the flourish  
443 of mountain tourism. In downstream towns – e.g. Bonneville and Annemasse – the expansion  
444 starts in the 1950's because of the economic attractiveness of Geneva.

445



446

447 Figure 6. Land use evolution and expansion demographic associated with impacts of  
448 Chamonix and Bonneville from 1848 to 2011 (© IGN).

449

450 Besides these numbers, the urban expansion and the growth in tourism come with the arrival  
451 of new residents in the valley (Haute-Savoie : la plus forte croissance démographique de



452 métropole, 2020), unaware of the local hazard history. The valley narrowness, the demand for  
453 land and the loss of memory of past events have led to build in historical flood-prone area,  
454 resulting in an increased exposure. For instance, in 1944 recently built houses in Chamonix  
455 were washed away by the Grépon River. The same situation also happened during the 1968  
456 flood that destroyed a new residential area in Bonneville. In Chamonix, the number of impacts  
457 punctually increase from year to year, somehow mirroring the population growth (Figure 6).  
458 Increasing exposure due to population growth and urbanization may then explain the  
459 increasing number of impacts. One can, however, notice the decrease in impacts after the  
460 disastrous 1996 flood event. This is due to the heightening of the dikes after the 1996 flood. In  
461 Bonneville, the link between the number of impacts and the population growth is not clear.

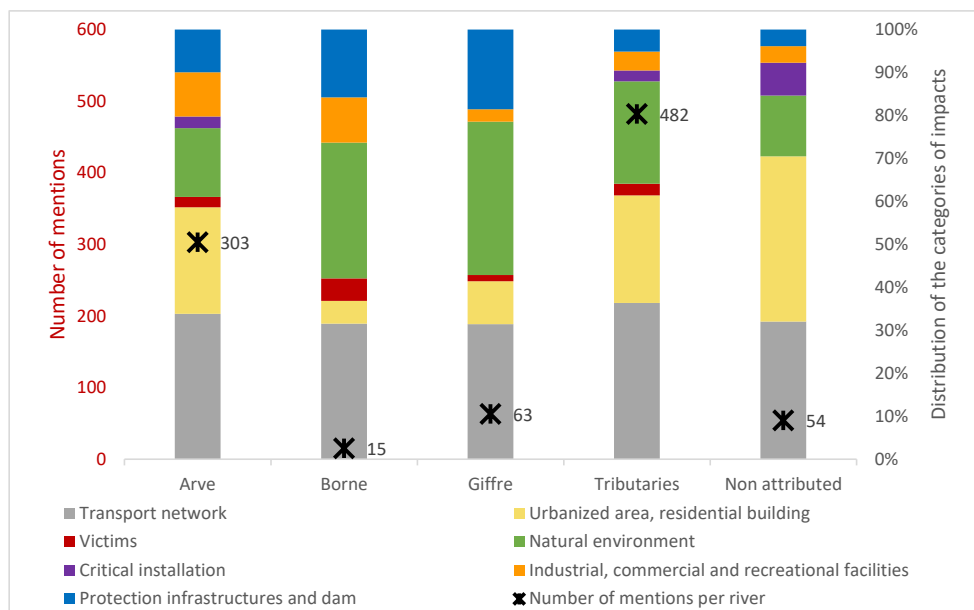
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#### 4.4. Nature of the flood impacts.

465 The quantitative analysis of text content reveals the distribution of the impact categories  
466 by river and illustrates the diversity of the catchment in terms of land use and economic  
467 development (Figure 7). This analysis of text content is particularly relevant because it allows  
468 to overcome the database scarcity of quantitative information on the severity of the flood.  
469 Indeed, it is difficult to estimate the severity of the flood event as the flow rate and the water  
470 height are only exceptionally mentioned. However, a link can be made between the impact  
471 nature and the severity of the event (Barriendos et al., 2019).  
472 The number of occurrences of the words determining the category is here named as the  
473 number of mentions. For the overall Arve catchment, damage to the transport network is the  
474 most frequent (406 mentions), followed by damage to urbanized areas (286) and natural  
475 environment (253). Impacts on transport network are in proportion equally distributed among  
476 river types (all around 30%). Impacts on industrial facilities are mainly caused by the Arve  
477 and the Giffre Rivers as their wider valleys allow the installation of these facilities. The Giffre  
478 and the Borne Rivers have caused the least impacts specifically on urban areas, probably  
479 because of less dense population and of an economy based on farming and tourism activities.



480



481

482 **Figure 7. Distribution of flood impacts according to the river types. The class “non attributed”**  
 483 **correspond to all impact with no assigned river (e.g. overland flows).**

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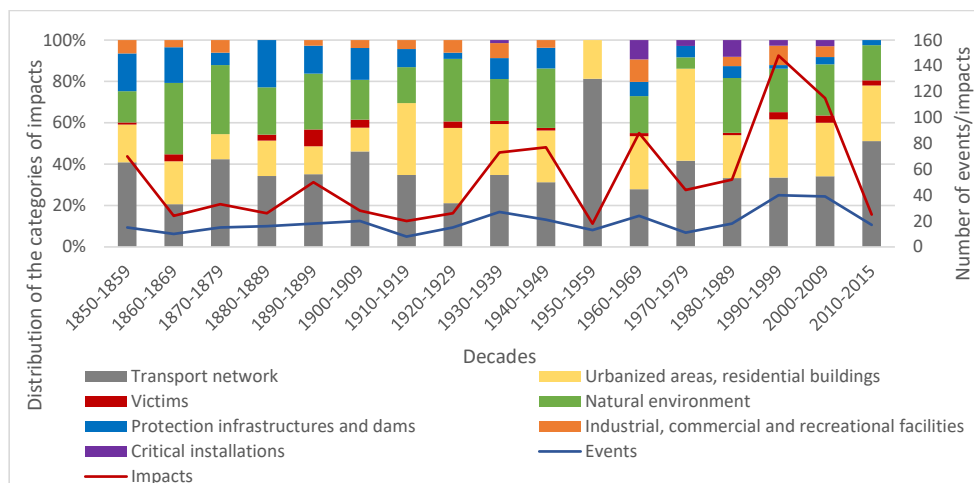
485 Most of the mentions of victims refer to impacts caused by tributaries (20 out of 28). They have  
 486 caused 80% of the deadly impacts registered since 1850 in the whole catchment, e.g. the 1892  
 487 glacial lake outburst and the 1987 flood of Grand-Bornand. The mentions of victims of the  
 488 Borne River should belong to the small tributaries class as the impacts occurred in the  
 489 uppermost part of the catchment. This high mortality may be due to sudden and strong floods  
 490 and to less developed infrastructure of flood protection on the tributaries.

491

492 To track potential changes in the nature of impacts since 1850, they are scrutinized by  
 493 decades over the last 165 years (Figure 8). Impacts on transportation networks are present in  
 494 every decade since 1850 but they increase after 1930 as well as impacts on urbanized area  
 495 and natural environment categories. It was not until 1960 that impacts on the industrial,  
 496 commercial and recreational facilities category increased. Mentions about critical installation  
 497 (sewers and water pipes) are recorded for the first time in the 1960’s. Mentions of victims are  
 498 present in almost every decade. Two decades (1950 and 1970) stand out in terms of category’s  
 499 distribution.

500 Nevertheless, no major evolution of the impacts categories can be seen, except the  
 501 emergence of mentions of critical installations in the 1930’s. The categories used for the  
 502 analyze have been inspired by a recent paper from Diakakis (2020) but in order to deepen our  
 503 analysis of the historical evolution of the impacts’ nature some other and more precise  
 504 classifications should be tested in the future as well as the evolution of the assigned words.

505



506  
 507 **Figure 8. Decennial histogram of the evolution of the categories of impacts divided by the**  
 508 **number of events.**

509  
 510 This analysis of proportions, however, hinders changes in absolute values. For instance, at  
 511 the catchment scale there is a slight increase in the number of mentions of the victims category  
 512 since 1980 (16 out of 28) (Figure 8). This increase is not easily noticeable when looking at  
 513 proportions of impacts categories because of the strong augmentation in the total number of  
 514 mentions since 1930. Yet, apart from the disaster in the Grand-Bornand in 1987, since 1931  
 515 all the mentions of victims refer to evacuations, recues or injuries.

516 The number of impacts has been almost multiplied by two since 1920. Hence, the mentions of  
 517 impacts on natural environment for the period 1850-1930 were multiplied by more than two  
 518 compared to the period 1960-2015. During the first period, mentions of impacts on natural  
 519 environment refer mainly to forest, field and crops, while after 1960 there is no mention of field  
 520 or crops and most of the mentions are about gullying, deposition of sediments and banks. This  
 521 is in agreement with the evolution of the land use due to the demographic growth, i.e. the  
 522 observed vanishing of forest areas and cultivated land to the benefit of urbanization (Figure 6).  
 523 Yet, mentions of impacts on urbanized areas during 1960-2015 has been multiplied almost by  
 524 four compared to the 1850-1930 period. This agrees with observed changes in land use  
 525 characterized by urban sprawl.

526

## 527 **5. Conclusions.**

528 We collected historical information from 1850 onwards to document flood impacts in  
 529 the Arve valley, an Alpine catchment characterized by a high hydrological and socioeconomic  
 530 diversity. The analysis of the HIFAVa database led to acknowledge the rise in the number of  
 531 impacts starting in 1920 and well-marked from 1960. This rise does not seem to be related to  
 532 increased flood hazard since it does not follow changes in flood occurrence, except partially  
 533 for the latest period (1990-2015). Instead, more frequent impact could be explained by  
 534 increased exposure related to the demographic growth (tourism and economic attractiveness  
 535 of Geneva) and/or by the evolution of the sources, in particular the emergence of the RTM.

536 There are two main types of flood events causing impacts in the catchment, e.g. floods related  
 537 to the main river and those related to the smaller mountain streams. Floods from these small  
 538 streams are characterized by sudden and fast hydrological responses and large sediment  
 539 transport, making hazard management difficult. They caused two third of the 916 recorded  
 540 impacts with numerous casualties and gathered impacts, such as the 1892 Bon Nant and the





541 1987 Borne rivers floods. In contrast, slow rising floods of the Arve River last in general several  
542 days, affect a large area and trigger mainly economics consequences and no casualties. The  
543 1968 flood affecting a large part of the Arve catchment is an exemplary case of this flood type.  
544 The analysis of the nature of the impacts does not reveal a clear evolution over the last 165  
545 years. However, further work is required to define more detailed categories allowing to  
546 question the evolution of the assigned words since 1850. Additional investigations of the  
547 municipal archives and interviews of local flood risk managers should also be undertaken to  
548 allow answering some key questions, such as the definition of high-impacts events in this very  
549 valley. The processes of risk memory transmission and the evolution of the local political risk  
550 management will be queried for the purpose of understanding the evolution of the social  
551 vulnerability. The following study of this database aim to better understand how hazard,  
552 exposure and vulnerability combines to trigger high impacts events across the recent history  
553 of the Arve catchment.  
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557 **Appendixes**

558

559 Table A1. List of the historical records – or their origin – used to provide information about flood events  
 560 and impacts collected in the HIFAVa database. The date mentions the year of publication for books  
 561 and period covered by the newspapers.

Manuscript materials	Printed materials	Newspapers	Other records
ADHS	AM Cluses	ADHS	BDHI
AM Bonneville	Conard 1931	Le Messager (1965-1968)	RTM (movie 1990)
AM Chamonix	Douvinet 2011	Le Dauphiné libéré (1963-2014)	SM3A
AM Cluses	Goy 2002	Journal de Genève (1855-1978)	
	Mestrallet 1986	La Croix 74 (1898)	
	Mougin 1914	L'Allobroge (1903-1940)	
	Parde 1931	Le Faucigny (1968)	
	Payot 1951	Le Figaro (1924)	
	PPR	Le Messager (1940)	
	PPRI	Le Mont-Blanc républicain (1903)	
	Rannaud 1916	Le Progrès (1898)	
	Rougier	L'Industriel Savoisien (1910)	
	RTM	La Revue Savoisienne (1887-1889)	

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564

565 Table A2. Presentation of the HIFAVa database showing its structure with each data entry.

id	[PK] serial	Primary key. ID number of an impact.
event	integer	Number of the event that triggers the impact. In case of an hydro-meteorological event, several impacts located at different places on different river are associated to the same event.
sources	integer	The different sources that provide information.
start_day	integer	Start day of event.
start_mont	integer	Start month of event.
start_year	integer	Start year of event.
start_date	date	Start date of event.
hour	text	Start hour of event.
time_unc	text	Uncertainty of the start date. H means that the start date is known at the hour scale, D at the day scale, M at the month scale and Y at the year scale. By default, when the day and/or the month is not known, "1" is attributed to start_day and/or start_month.
duration	real	Duration of event
river	text	River that trigger the flood (the cell may be empty if the impacts are not related to river flooding).
impact	text	Nature of impact.
municipality	text	Municipality where the impact is located.
imp_lat	real	Latitude of the impact in decimal degrees.



imp_long	real	Longitude of the impact in decimal degrees.
Space_unc		Describe the spatial scale of impact location. A means that the impact is located at the scale of a point on a map, B at the scale of a part of a city, C at the scale of a city, D at a coarser scale than the one of a city.
count	integer	Number of victims
hydrometeo_descript	text	Description of the hydrometeorological event according to the sources.
precipitation	real	Precipitation rate given in the sources (mm).
flood_descript	text	Description of the flood from the sources
river_water_level	real	Water level of the river (m).
water_level	real	Water level of flooded area (m).
discharge	real	Discharge of the river (m3/s)
impact_descript	text	Description of the impacts according to the sources.

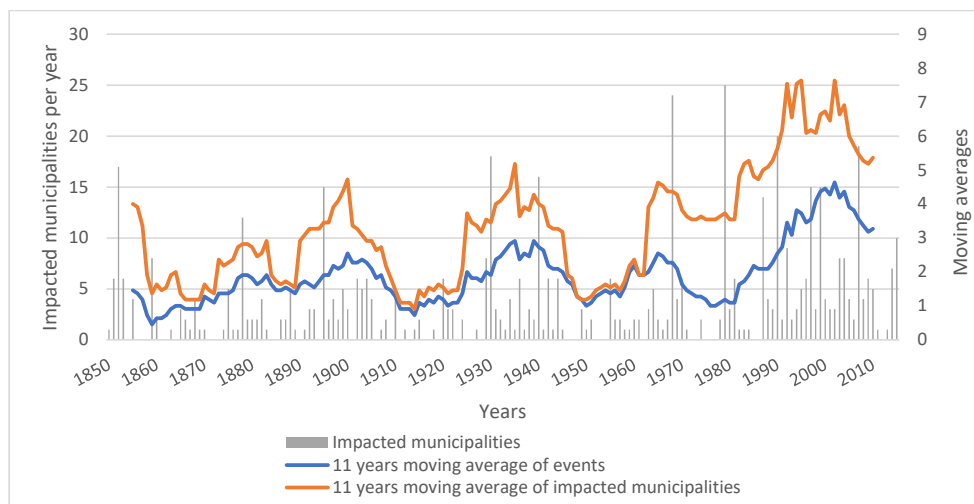
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568 Figure A1. The wiped-out thermal bath of Saint-Gervais after the debris flow of the 12th of July 1892  
 569 (Thermes de Saint-Gervais Mont-Blanc, 2021).



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Figure A2. Occurrence of impacts and moving averages of impacted municipalities and associated flood events (one line = one municipality impacted by a flood event).



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