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# Hydro-climatology of the Lower Rhône Valley: historical flood reconstruction (AD 1300–2000) based on documentary and instrumental sources

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**ABSTRACT**
From the HISTRHONE database we extracted 1483 hydro-meteorological events from AD 1300 to 2000 that occurred in the Lower Rhône Valley, France. Daily heights of the Rhône River at Beaucaire and Arles are also available, from 1816 and 1829, respectively. A total of 517 floods were divided into three categories and a synthetic frequency severity index (FSI) was computed. Running averages of 11 and 31 years show a succession of poor and rich flood fluctuations. Extreme floods tripled in the second half of the period (1650–2000). Singular spectrum analysis isolates a dominant irregular component (main positive anomalies in 1450–1580, around 1700, late 18th century, and most of the 20th century). We focus on the 17th century, with rare flooding events between two secular so-called "hyper phases", i.e. frequent and/or severe floods. We also recorded 173 episodes of ice in the river, during the Little Ice Age.

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## 1 Introduction

The Rhône River, while not the longest, is the mightiest river in France (highest discharge at Beaucaire) (Fig. 1). This paper analyses its downstream and Mediterranean section (i.e. the Lower Rhône Valley, LRV), from the town of Orange to its delta and mouth in the Camargue (Fig. 1). Our study runs from AD 1300 to 2000, with a focus on the Little Ice Age (LIA). Until now, this river has not been studied over such a long period, as has been done for the rivers of Central Europe (Brazdil 1998, Glaser 1998, Brazdil *et al.* 1999, 2006, 2010, 2014, Glaser and Stangl 2003, Mudelsee *et al.* 2004, Böhm and Wetzel 2006, Glaser *et al.* 2010, Schmocker-Fackel and Naef 2010), Catalonia and Spain (Barriendos and Martin Vide 1998, Benito *et al.* 2003, Llasat *et al.* 2005, 2013), or Italy (Camuffo and Enzi 1996), and for the Rhine basin and the Dutch Rhine delta (Glaser and Stangl 2003, Wetter *et al.* 2011). British historical records have improved understanding of high-magnitude floods (Macdonald 2014). Such studies provide good chronologies on the poor and rich phases of floods in Northern Europe and in the Mediterranean peninsulas. The great French rivers have only old compilations (Champion 1858–1864). A few tributaries of the Rhône River have been studied over a long historical period: the Isère (Cœur 2008), the Ardèche (Naulet 2002). An institutional study in France (Lang and Cœur 2014) established lists and characters of the noteworthy floods, but they are simply lists, without statistical purpose. Nevertheless, the riverside towns in the LRV possess considerable documentary resources, but much time and patience is needed to study them. The skills of historians are needed for this research in a wide range of archives, libraries and official or technical agencies.

An early paper (Pichard 1995) contains a short overview of this documentation and presents the first results of this survey. The analysis was then continued in two PhD theses of Pichard (1999) and Roucaute (2008). In 2011, a comprehensive database was compiled at the Centre Européen de Recherche et d'Enseignement des Géosciences de l'Environnement (CEREGE), Aix-en-Provence, France, and the results disseminated through the HISTRHONE database (http://histrhone.cerege.fr/). This database focuses on hydrology (flood, high or low water level), climate (moving or blocking ice, heavy rainfalls and droughts, invasions of locusts) and on impact (damage to urban and rural areas and infrastructure). All these observations were indexed by year and location, with details about the damage that occurred in the towns, villages, valleys and plains and to infrastructure. For each year, the records and texts were transcribed. Two databases for ice and drought complement the main database. A

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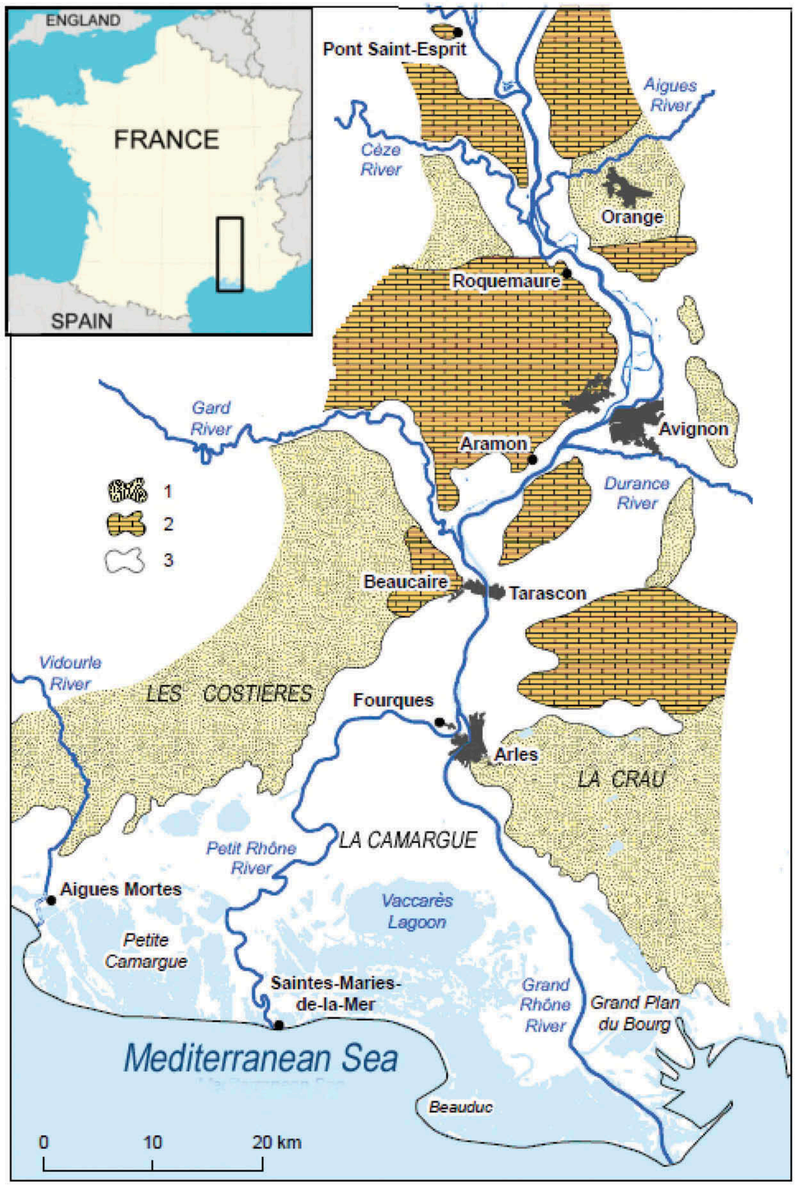


**Figure 1.** Location of the Rhône catchment and the area studied.

**Legend**. 1: Pleistocene terraces and fans; 2: resistant geological substrate; 3: recent alluvium of the Rhône River and its tributaries. Black areas denote actual urban areas.

detailed chronology covers the period 1226–2000, and allows us to cross-search on a long or a precise period with a synthetic overview. The great flows of the Rhône River were mapped by the SIGéo laboratory at CEREGE. A book (Pichard and Roucaute 2014a) drew the first conclusions from this historical inquiry.

Our main goal here is to present some results of this historical investigation, conducted in the archives and libraries (documentary sources) and among the instrumental data, which have been combined into a comprehensive database. The water heights of the Rhône River have been measured continuously since 1816 at the single and stable scale in Beaucaire, which has stayed in the same place with the same zero mark from 1816 to date. The measurements have been noted in Arles since 1829 at different scales, with a previous period of daily measurement from 1783 to 1788 by Dr Louis Bret.

We focus on the large fluctuations during the seven centuries from 1300 to 2000. As advocated by recent statements (Hall *et al.* 2014), flood frequency in the long-term perspective highlights "rich" and "poor" periods of flood occurrence and magnitude. However, the abundance and precision of data allow us to construct a frequency and severity index (FSI) for the entire series of events (see Section 3.2). This study could subsequently be used to improve the frequency curve estimation (Kjeldsen *et al.* 2014). But the interpretation of these variations is complex and requires the cross-referencing of data and metadata of structural and external factors: primarily, meteorological factors including rainfall and, to a lesser extent in the LRV, the melting of snow, which played a primary role in the input of water in the whole catchment basin. Modes of atmospheric variation, including the North Atlantic Oscillation (NAO) (Jacobeit *et al.* 2003), and volcanic events or variation of the solar constant (Barrera-Escoda and Llasat 2015) modulate rainfall variability. But the frequency and/or severity of floods are also determined by the changing geometry of the riverbed, by the flow mode, or primarily by anthropogenic actions in the catchment. These points are discussed herein, allowing a future climatic interpretation to be established on solid foundations.

## 2 Search for the data predictors

In the studies mentioned above, the abundance of historical sources is often described in detail. There are common features in specific historical documents on floods and hydrology. Here we focus on the local traits of sources in the LRV. The majority of the useful documentation is found in towns and cities, particularly Avignon, the seat of the papacy during the 14th century, Tarascon, Beaucaire and Arles (Fig. 1). These old towns are good conservators of history. There are thousands of manuscripts of local interest for the researcher in their libraries, and their archives are extensive.

### 2.1 Before technical and instrumental observations, huge quantities of documents

The study of floods in antiquity and the Early Middle Ages requires collaboration between specialists in archaeology and geomorphology to identify periods of flooding of the Rhône River, in particular, periods of hydrological calm and periods of high flood severity and frequency (Bruneton *et al.* 2001, Allinne 2010, Wilhelm *et al.* 2012). The subsequent period (10th–13th centuries) is not well investigated, so we cannot say whether it was a period of little flooding (Champion 1858–1864, and remarks of Bravard 1989). From the 14th and 15th centuries, documentation becomes more abundant and its characteristics persist until after the 18th century. This is mainly due to records being kept by local authorities in villages and especially towns. As almost everywhere, the municipal reports produced a first list of floods through allusions, or sometimes circumstantial details given by mayors and consuls. But one feature of the communal and town sources in southern France must be underlined here: the deliberations are usually supplemented by municipal accounts. In particular, these accounts include receipts for the repair of dikes or daily payments for the *levadiers*, the corporate workers responsible for dikes since the Middle Ages. Other expenses include subsistence costs for citizens called out by the tocsin (alarm) in times of flood emergency.

Other specific sources in the LRV include family manuscript records, called *livres de raison* (ratio = accounts), private journals or *diaires*, and day-to-day notebooks. These were first written by the few educated people, such the surveyor of Arles Bertran Boysset (*ca.* 1355–*ca.* 1415), and then by landowners, nobles and burghers. For example, a dozen successive *livres de raison* of the De Mandon family, owners of land along the Rhône River south of Arles, cover almost 250 years from the 16th to the 18th century (Pichard 2010).

In addition to these private sources, notaries have left tens of thousands of annual registers that are kept in the official archives in the south of France. Some of them contain references or brief notes on floods or other climatic events, but their exploration is not easy, except when the notary noted the yearly climatic events, at the beginning or the end of the register. For example, the notary Jean Peyrat, at Orange, left annual notes from 1518 to 1567.

Annals were written by the same notaries, and also by town clerks. Other annals come from local scholars and historians. The papal annals of Avignon may be included in this category. They are known under the title of *Vitae paparum avenionensium*, edited in 1693 by Baluze and republished and reviewed by G. Mollat in the 20th century. Baluze and Mollat (1916–1928) reported historical events, including floods, over the 70 years when the popes ruled *ad ripas Rhodani*, on the banks of the Rhône River. The towns of Avignon and especially Arles had a long tradition of local annals lasting until the 19th century. There are many notes about climate, but it is necessary to check and cross-check them with other documentary sources.

At a higher administrative level in the hierarchy of power, in the French *Ancien Regime* are the provinces and state government administrations (papal legates in the *Comtat Venaissin*, or provincial "intendants" in Provence, Languedoc and Dauphiné). The same applies to the provincial state archives, with special record sections about rivers (Rhône, Durance) and a large number of letters and reports on extreme events, storms, rains and floods. A general policy concerning risks was gradually established, continued and even increased in the departments during the French Revolution (1791–1797), conducted by the departments' directories (*directoires* in French) and then, in the Napoleonic era, by the prefects and the councils (*Conseil Général*) of the departments. Their role became essential during the 19th and 20th centuries. Printed and handwritten documentation produced by the prefectures and departments include such essential data as yearly reports by engineers on the state of the rivers, or on flooding and the state of the dikes. A special Rhône service was set up in 1840 which included local engineers and working conductors in the cited *Ponts et Chaussées* administration (see Section 2.2), whose principal agency was located in the city of Lyon.

Outside the centralized state structures described above, private or partly private associations of defence against the Rhône and Durance rivers existed from the 13th century at Arles and the Camargue, in the Rhône Delta. Elsewhere, princes, nobles and religious communities assumed responsibility for the construction and repair of dikes on their demesnes and territories. These territorial associations were often in conflict. In 1542–1543, a first organization was imposed on the deltaic associations of the Camargue by the municipalities concerned by the increasing number of floods. In 1807, the Napoleonic state imposed a strengthened organization for these associations that lasted until about 1849. These associations left a large number of documents, recently given to the municipal archives of Arles.

A great variety of sources and records still exist in libraries and official archives. Ecclesiastical records from the cathedral chapters and the offices of bishop and archbishops are important. The French Revolution seized and centralized these archives in the departments. Here we found references to processions to stop or solicit rain (*pro pluvia*). The archives of families or scholars can eventually find refuge in public archives. Feudal archives contain much information on floods and extreme climate events (e.g. the rich archives of the county of Caderousse, a little town on the Rhône, south of Orange),

## 2.2 Technical and scientific records

Technical archives come from the agencies responsible for measuring the daily heights of the Rhône River (and from the late 19th century, computing the discharge), and also those that maintain the dikes and are concerned with flood prevention. This role was given in France to the Ponts et Chaussées administration, organized in the 18th century. In 1747, the School of Engineers was created and later, in 1795, for graduates from the Ecole Polytechnique. In the LRV, François Poulle, an engineer in Arles, was a prolific cartographer, and the witness of many climatic events and floods, from 1810 to 1840. Many other prestigious colleagues pursued his work during the 19th century.

Historically, the water levels were only estimated by sight by mariners, who left no written evidence. Harbour quay walls and their stairs served as benchmarks at Arles and, in 1693, the municipality added metal marks at different critical heights to warn the town of harmful floods. In the same town a learned notary, Pierre Véran (1744–1819), left many documents and registers on the history of Arles and the Rhône and its floods, as well as other climatic events. In 1806 he drew an *échelle hydraulique*, a hydraulic scale, marking the levels from the old marks of floods found on houses and city walls since 1530, now largely disappeared (see the HISTRHONE database: Ressources/Synthèses/Hauteurs et altitudes aux échelles du bas Rhône). This is a fundamental source for the history of floods in the town of Arles. Elsewhere in the LRV, other hydraulic scales called *Rhônomètres* were erected to measure the heights of the waters, often situated at the water intake channels on the Rhône River. The main scale was established in 1816 at Beaucaire (Fig. 1), and provided the longest, most stable and valuable hydrological records of the height of this river.

Since 1840, after the most catastrophic flood, three measurements have been made every day at 07:00, 12:00 and 17:00 h (against a single measurement made at 12:00 between 1816 and 1840). At Beaucaire, the Rhône River has its maximum annual *module* (that is to say, mean annual discharge more than 1700 $m^3/s$), hence the great interest in this long series of daily measurements.

## 2.3 Environmental sources

To understand the evolution of a hydrological system, prior knowledge of the evolution of the riverbed and that of the complex catchment of the river is needed. For the Rhône River, documentation for the first is found in the old cartographic and textual sources, taking advantage of new geo-archaeological methods (Arnaud-Fassetta 2000, 2009, Arnaud-Fassetta *et al.* 2010). Beyond a search for the occurrence of floods, an analysis in which the forcing factors interact with the climate and surface or subsurface hydrology is needed. These factors include the demography, urban and rural development and land use. In the Mediterranean environment, erosion and alluvial transportation are important factors in the hydrological evolution, especially during the LIA, when one or more changes in the fluvial braided style and hydrology occurred. This change was called "metamorphosis," in a figurative sense, by Bravard (1989) and the concept was widely adopted in successive geomorphological studies. The documentary sources of this environmental context are of considerable scope and are specific according to each region. For the French Mediterranean area, the physical, environmental and historical studies for the Late Middle Ages and Modern era are still few and isolated (Pichard 1999, Roucaute 2008). Thereafter, the context of the climate of the past becomes better known (Lionello *et al.* 2006). Documentary material (a chronology of ice and a chronology of droughts) has been gathered in the HISTRHONE database. The first results were synthesized in Pichard and Roucaute (2014a) and in a special issue of *Méditerranée* around the theme of the Little Ice Age in the Mediterranean (Pichard and Roucaute 2014b, Pichard *et al.* 2014c). Further detailed studies are needed to understand the impact of river management in the catchment and in the river bed. Dikes have existed since the 12th century, and these have been especially strengthened since the 19th century, with a strong impact on the riverbed, and perhaps also on the flow. This is an important issue to discuss in a separate paper.

### 2.4 The overall volume and statistical distribution of the documentary data

The database of the LRV brings together a large number of highly varied documentary sources. There is a total of 1547 sources, counting only those giving useful elements for the database, but not including the systematic survey of daily water heights from 1816 to 2000. These useful sources themselves have supplied 4982 references, on average 3.2 citations or *items* per source and 3.4 by event (but hundreds in some extreme cases, e.g. the 1856 flood). Sources from the 19th and 20th centuries provide more specific and quantitative information. To offset the imbalance, a much greater number of documents was included for earlier periods (Fig. 2).

## 3 Methodology

The above data come primarily from the database HISTRHONE. But here we must extend and complement our methods and focus on hydrological and climatic variations.

### 3.1 Flood classification

Many types of flood are noted: from the lowest to the highest floods,  since the high water which do not overflow to "extreme" floods. Likewise, river ice is classified into floating ice (61 occurrences) and blockage ice (101 occurrences). We also document other data related to climate, such as storm flooding, marine submersion, droughts, locust invasions and metadata on the gauges of rivers, rating curves or levelling methods.

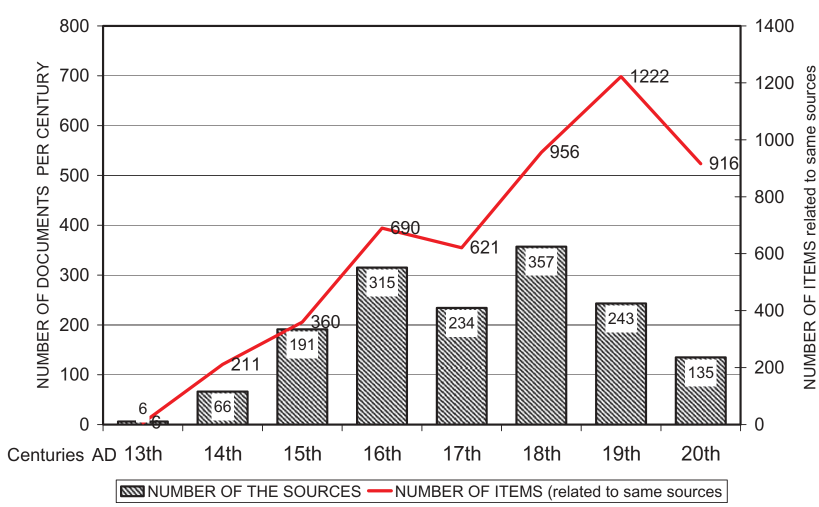


Figure 2. Distribution of useful documentary sources by century (histograms) and total hydro-climatic events obtained by century or item (line). Daily observations of measured water levels (1783–1788 and 1816–2000) and other instrumental data are not included. Sources are growing in density and productivity towards the 19th and 20th centuries.

Flood classification should consider the topography of the LRV, which has a wide floodplain expansion (distal plain), particularly in the Camargue Delta; and also the situation of towns that face each other across the river, such as Avignon–Villeneuve or Tarascon–Beaucaire. Downstream from Beaucaire, the river divides into two branches, with two towns located on the fork (*diffluence*): Fourques on the smaller branch, or Petit Rhône (14% of the flow), and Arles on the Grand Rhône (86% of the flow).

Two criteria have heuristic value over the seven centuries:

(i) The overflow is a valuable criterion due to the relative lateral stability of the riverbed narrowed by quays and urban walls from the Late Middle Ages, including at Arles. However, the river in this town has gradually excavated its bed since 1875. The possible narrowing of the riverbed deltaic section is a historically dated fact (Late Middle Ages).

(ii) The maximum lateral and longitudinal expansion of overflows in the plains and delta to the topographic distal limits, and even "to the sea", as expressed in the sources. Such extreme events happened during the well-known and damaging overflows of 1840 and 1856, when villages and towns were flooded. This criterion is used to define extreme floods C4 (see Table 1). High water (or C1 *crue*) is the lowest category and takes place without overflow. A simple (or localized) slightly damaging overflow is referred as a C2 flood. The intermediate but destructive floods (C3) come between C2 and C4 on the criterion of damage caused and by their lateral/longitudinal extent.

**Table 1.** Number of events of every type for the 1226–2000 period.

| Century | C0 | C1 | C2 | C3 | C4 | Cd | Ci | GA | GF | Gi | IP | SM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 13th | 1 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| 14th | 8 | 2 | 1 | 23 | 2 | 4 | 5 | 7 | 0 | 1 | 0 | 0 |
| 15th | 10 | 11 | 33 | 30 | 2 | 12 | 8 | 4 | 1 | 3 | 3 | 0 |
| 16th | 13 | 27 | 45 | 26 | 5 | 15 | 20 | 8 | 1 | 1 | 8 | 0 |
| 17th | 8 | 6 | 25 | 15 | 2 | 19 | 14 | 19 | 4 | 2 | 7 | 3 |
| 18th | 20 | 36 | 55 | 20 | 5 | 10 | 9 | 27 | 8 | 5 | 22 | 2 |
| 19th | 115 | 165 | 42 | 17 | 10 | 2 | 1 | 30 | 31 | 0 | 6 | 2 |
| 20th | 60 | 198 | 62 | 13 | 10 | 0 | 0 | 6 | 16 | 0 | 2 | 1 |
| *Total* | 235 | 445 | 263 | 145 | 36 | 72 | 58 | 101 | 61 | 12 | 48 | 8 |

**Notes**
C0: annual low water level. Before the 19th century, only the extreme lower water level appeared in the documentary sources (see Section 6.5).
C1: High water level or "Gros Rhône" without overflowing. Up to the 18th century (except from 1783 to 1788) accounts of the C1 type are not exhaustive in the documentary sources.
C2: Simple overflow above the banks but not severe and/or with minor and local expansion.
C3: destructive flooding, of intermediate severity between C2 and C4.
C4: Extreme and disastrous flooding.
Cd: Floods with only indication of overflow, without explicit explanation.
Ci: Floods of unspecified severity.
GA: River blocked by ice.
GF: Floating or moving ice in the river.
Gi: River ice without specific character.
IP: Rainwater flooding.
SM: Intrusion of the sea over the land (catastrophic storms only; a more complete study is necessary for this coastal phenomenon).

On the criterion of damage (as exemplified by Barriendos *et al.* 2003), it should be noted that the LRV did not have any stone bridge before the 19th century (except at Avignon where the Saint Bénézet bridge was often damaged from the time it was built; upstream, the bridge at Pont-Saint-Esprit is north of the section studied here). Boat bridges were commonly used. The C3 destructive floods demolished and dragged bridges away, particularly when accompanied by the frequent occurrence of floating ice.

There is a total of 889 well-dated and referenced *crues* and flood events in the Lower Rhône River from the 14th to the 20th century. For the 14th to 18th centuries, we must add 130 Cd and Ci floods. These are less reliably dated (year only) or lack sufficient documentation. Many were rejected, although referred to as such in the database (Table 1). The Cd floods are well-proved overflows but without good specification on their extent and severity (72 cases, partly uncertain), while Ci are *crues* without certainty about overflow or severity (58 cases).

### 3.2 Flood frequency and severity index (FSI)

The richness of the documentary sources allows us to establish a time series of frequency and severity of floods to be compatible and comparable with the measured data (height and discharge) of the 19th and 20th centuries. We are searching not only for extreme flood events but also for those of moderate severity, so that we can extrapolate the strength or weakness of the "hydrodynamic model" of a given period, that is rich or poor periods of floods. In addition, references to "high waters" without overflowing are only partially reported before 1816. Thus, it is better to use the C2, C3 and C4 flood categories, which are probably homogeneously reported throughout the whole period, except for the simple or local overflows (C2), which only appear in the sources from the 15th century.

We tried to weight the C2 to C4 flood categories by assigning a coefficient of severity on the average discharge for each. The only reliable assessments are extracted from the 20th century database Banque Hydro (www.hydro.eaufrance.fr/). Approximate threshold discharge for each flood type is shown in

**Table 2.** Calibration (as severity index) of the three types of floods using the discharge averaged from 25 floods of C2 type (between 1920 and 1960) and the averaged flow for C3 and C4 type floods. The index for C4 floods is calculated on C2, not on C3, flood discharge.

| Type of flood | Discharge threshold | Severity (index) |
|---|---|---|
| C2 | 5200 $m^3/s$ | 2* |
| C3 | 7200 $m^3/s$ | 2.77 |
| C4 | 9000 $m^3/s$ | 3.46 |

*The index 2 for the floods of C2 type is a pure convention, for simplicity. But C3 and C4 flood indices are calculated proportionally from the average discharge. Furthermore, for the Cd- type (overflow with intensity unknown or not well understood in the medieval and early modern times; see Table 1), we choose the index 1 as a simple convention.

Table 2 and translated into severity indices. A frequency–severity index (FSI) is then simply built as the product of the frequency by the relative severity index of each flood type. The sum of FSI for C2, C3 and C4 floods characterizes the richness or poverty in floods and the hydrodynamic model for each year or decade, according the case. The FSI refines flood variability based solely on frequency. Comparison with the 20th century discharges at Beaucaire was carried out only after a preliminary classification of C2, C3 and C4 floods of the same period. The average discharge of each category of floods was then examined. Indices are only a simplified representation of the severity of each flood type. If C2 = 2, C3 = 2.77 and C4 = 3.46. $Q_2$ (5200 $m^3$/s), $Q_3$ (7200 $m^3$/s) and $Q_4$ (9000 $m^3$/s) can only be regarded as approximate thresholds between three types of floods.

To sum up this approach, the FSI is the sum of the product (multiplication) of flood frequency and its respective severity. Indices are simply added (cumulative index) for each unit of time that is used (year, decade or more):

$$\mathrm{FSI} = N_2 2 + N_3 2.77 + N_4 3.46 \qquad (1)$$

where $N$ is the flood frequency or number of floods per unit of time (year, decade or more), and the subscripts 2, 3 and 4 denote the flood types C2, C3 and C4.

The goal is to determine the flooding severity of each period, and even the hydrological dynamics of each period (given the amount of information). A different purpose will be to determine the likely maximum discharge of each *crue* at the scale station.

### *3.3 Methodological filtering*

To reinforce the basis of the following analyses, several methodological filters are implemented. The reliability of the old data is ensured by taking into account the cultural context (the Julian or Gregorian calendar) and the history of data transmission from original source up to the present day, correcting incorrect versions if need be. Criteria for the data values can be quite different depending on the various contexts. It is sometimes necessary to go back over the transmission process and, if possible, to find the original statement. The data are sometimes indirect, such as work on the repair of dikes, deliberations for carrying out these repairs, borrowing to finance them, or putting the work up for auction.

Personal testimonies, as described in Section 2.1, have some degree of subjectivity, but they are valuable in the details they provide, including the accuracy of dates of events. For earlier periods (Late Middle Ages and Early Modern period) accuracy to the month is satisfactory (Table 3).

A second filter is introduced with the systematic organization of events in the database in standardized form. A third filter corresponds to all metadata validation and explaining the hydrological change. In HISTRHONE a detailed chronology makes possible an annual synthesis of the data, measured rainfall since 1728, storms, prolonged rains, droughts and ice events, from documentary sources.

## 4 Results

Analysis for seven centuries requires consistency of data. Ordinary high waters (C1) are completely identified only from the 19th century, and have been provisionally excluded. Consequently, Figure 3 represents the decennial frequency of C2, C3 and C4 floods. Figure 4(a) represents the FSI annual cumulative indices of C2, C3 and C4 (as indicated in Section 3.2) and Figure 4(b) shows the 11-year and 31-year running averages of FSI.

**Table 3.** Accuracy of dating and precision of the documentary data of floods, all types combined, during the pre-instrumental period. Precise dating to the day is provided for the C2, C3 and C4 types in particular. After the 18th century, because observations were made daily, the accuracy is complete. For many floods, the instantaneous maximum will be estimated to one hour at least.

| Century | Years only | Years & months only | Years, months & days | Total floods |
|---|---|---|---|---|
| 14th | 4 | 27 | 6 | 37 |
| 15th | 2 | 83 | 11 | 96 |
| 16th | 2 | 108 | 28 | 138 |
| 17th | 11 | 38 | 32 | 81 |
| 18th | 0 | 76 | 60 | 136 |

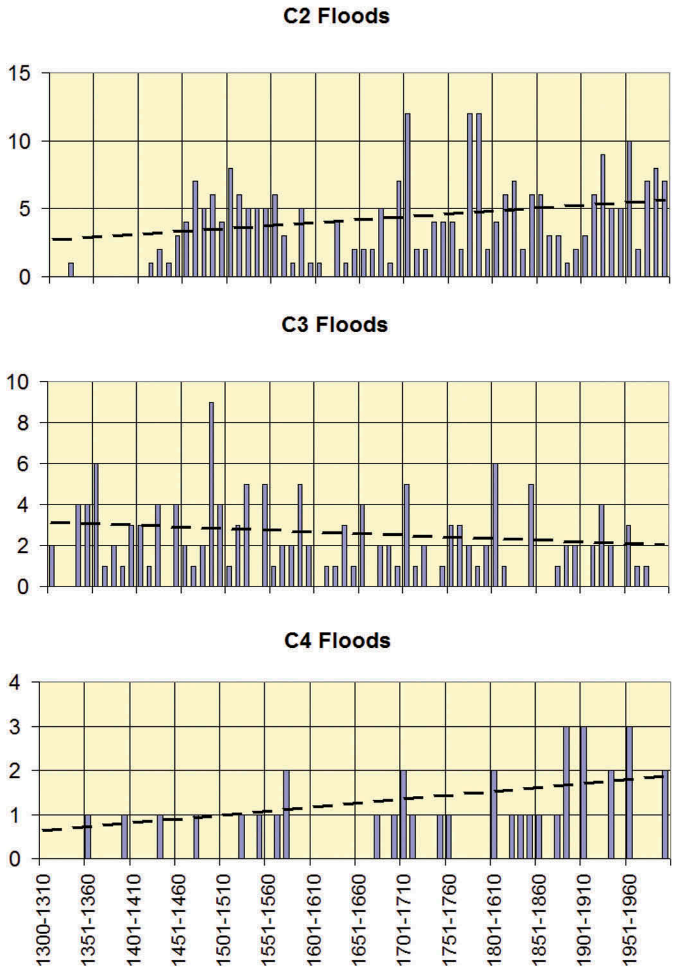


**Figure 3.** Number of floods (C2, C3 and C4 types) per decade (bars) and mean linear trend (dotted line). The *y*-axis represents the number of floods (C2, C3 or C4) by decadal occurrence.

**Note**: C2 floods (simple overflow of little severity and/or simply local) are not representative before the 15th century.

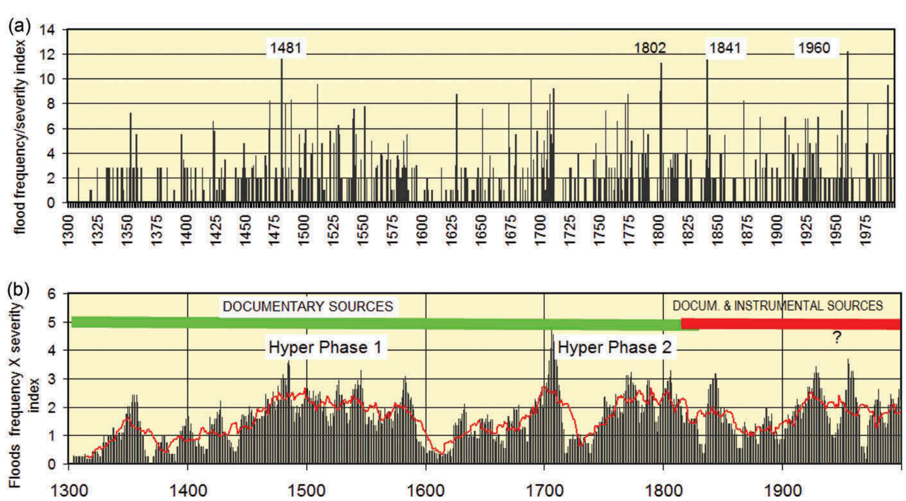


**Figure 4.** Annual cumulative frequency severity indices of flood and FSI running average: (a) annual FSI index (*y*-axis), and (b) FSI index (*y*-axis). The black area represents the cumulated annual FSI calculated with an 11-year running average, the curve shows the 31-year running average. After 1900, the question mark (?) expresses the uncertainty about the existence of a third hyper phase.

### 4.1 Distribution in flood frequency and FSI

The decadal distribution in flood frequency (Fig. 3) and smoothed FSI curves (11- and 31-year) (Fig. 4) are discussed here.

Non-destructive C2 floods are well recorded from the 15th century only, but are more frequent from 1450 to 1560, a period during which the simple, more or less damaging overflows occur 61 times in 111 years (Fig. 3). The C2 frequency is almost as great from 1690 to 1860 (98 times in 170 years), but seems irregular and heterogeneous. During the 20th century the frequency is still relatively high. The general upward variability (dotted line) is not completely representative due to large periods of low frequency during the 17th century, first half of the 18th century (1712–1754) and 19th century. In contrast, the C3 and C4 categories of floods show a high but opposite long-term trend. The C3 floods are frequent until the 16th century, which explains most of the hydrological dynamism of this period. As can be seen, the FSI of the C3 floods is unusually high during the first half of these seven centuries (Fig. 4), while the extreme C4 floods were rare at this same time, but contribute largely to the flood dynamics from the 18th century onwards. In total, in terms of cumulative FSI, all types of flood event have undoubtedly increased over the last three and a half centuries, mainly due to extreme C4 flooding during the 19th and 20th centuries: nine C4 floods from 1300 to 1650 and 27 from 1651 to 2000, an exact threefold increase (Fig. 3, C4 floods and Table 4).

### 4.2 Fluctuations and peaks of FSI

Figure 4(a) shows the irregular annual movement of cumulative FSI for any type of flood (including C1) and Figure 4(b) shows the slow fluctuations determined by the 11- and 31-year running averages. Prior to cyclical and statistical analysis, these curves show three types of variations.

(i) Inter-annual variations appear: over one year, peak of floods occurs apparently with irregularity. The years having an annual FSI higher than 11 or 12 imply several successive severe floods. In 1481 (FSI: 13.08), three C3 and one C2 flood(s) occurred from May to December. In 1802 (FSI: 11.31), three distinct damaging C3 floods and one simple C2 overflow occurred from January to March. In 1841 (FSI: 13.08), three C3 and one C2 flood(s) occurred from February to December, and in 1960 (FSI: 12.23), three C2, one C3 and one C4 floods occurred from January to November. (Further details and documentation are available in the HISTRHONE database.)

(ii) Figure 4(b) shows clear fluctuations of FSI with alternating increases and decreases (running mean over 11 years). Statistical verification is discussed below. The 31-year running mean (red curve on Fig. 4(b)) shows the major phases of rich or poor hydrological dynamics. The first and clear deterioration (i.e. rich flood period) occurred in the 1350s. After a calm period, contemporary with important economic and demographic depression after the Black Death of 1347, recurrent floods appeared after 1420 and increased after 1450 to reach their peak in the 1480s (Fig. 4(b)). This is the second decadal peak for the FSI during the LIA period (FSI cumulative index: 38 *vs* 48 for the 1700s; see below).

(iii) Until 1587, long periods of high frequency of floods were recorded, called here Hyper Phase 1. This is a third category of long fluctuation, similar to a secular trend. For most of the 17th century, a long depressed flood phase followed, which is subject to further discussion. But in the Late Maunder Minimum (1674–1711), a sudden increase of flooding occurred (Fig. 4(b)). This unprecedented peak in FSI of floods (cumulative index: 50 from 1701 to 1711) clearly indicates the return of a second hyper phase. With four or five large fluctuations in FSI of floods, this Hyper Phase 2 is contemporary with the coldest period of the LIA (see Section 6.6). After another depressive period (1875–1906), the 20th century was again a rich period of floods until the 1950s, a decadal fluctuation similar in FSI terms (cumulative index: 38.6) to those of the LIA period.

**Table 4.** Cumulative FSI of floods in the first and second parts of the entire series. The increased FSI after the 17th century is mainly due to the extreme C4 floods. This evolution is certain, because the period of abundant and less severe C3 floods (Fig. 3) up to 1650 must necessarily include records of C4 floods also.

| Cumulative FSI | | |
|---|---|---|
| C3 floods | C4 floods | Total (C2+C3+C4) |
| 235.5 | 174 | 440.5 |
| 163.4 | 354 | 610.6 |

## 5 Long-term trend and quasi-periodic oscillations

Time series of inter-annual flood indices are analysed using classical fast Fourier transform (FFT) and singular spectrum analysis (SSA). The FFT simply converts time series to the frequency domain through its decomposition into components of different frequencies (Fleming *et al.* 2002). The power spectral density (PSD or power spectrum) describes the distribution of power (analogous to variance) into frequency components. The SSA (Bromehead and King 1986, Ghil and Vautard 1991, Vautard *et al.* 1992, Ghil *et al.* 2002) considers the discrete time series of inter-annual flood indices and its successive shifts by a lag parameter, called the embedding dimension ($M$). The multivariate set of observations is then subjected to eigen decomposition (as in principal component analysis) so that the original time series is decomposed into a small number of slowly varying components (i.e. trend), periodic and quasi-periodic components (associated with pairs of similar eigenvalues) which can be modulated in amplitude, and noise. In contrast to FFT, which is based on fixed sine and cosine functions, SSA uses a data-adaptive basis without any *a priori* assumptions about the parametric form of the slow and quasi-periodic components of the time series. The SSA thus provides data-adaptive filtered versions of the original time series called reconstructed components (Vautard *et al.* 1992, Ghil *et al.* 2002). The sum of all reconstructed components is equal to the original time series. The main goal of the FFT and SSA analyses is to extract the main trend and/or periodic/quasi-periodic components of the inter-annual flood indices from 1300 to 2000.

Figure 5 shows the PSD of the FSI (upper panel) and all floods minus category C1 (lower panel). Both time series are highly similar (correlation = 0.94) and, as a consequence, their PSD matches almost perfectly. There are broad spectral peaks near 2–3, 4–5 and 14–15 years. The spectrum is also significant for periods longer than ~100 years. The FSI is subjected to SSA with an embedding dimension of $M$ = 30 years. One irregular component (first eigenvector) and three pairs (eigenvectors 2–3, 4–5 and 8–9), corresponding broadly to the three quasi-periodic oscillations revealed by PSD, are significant at the one-sided 90% level according to Monte Carlo simulation (Allen and Smith 1997). Figure 6 shows the reconstructed components corresponding to these eigen elements (Vautard *et al.* 1992). The longer-term variation (Fig. 6(a)) is an irregular component, including a weak increasing non-linear trend, without any clear periodic oscillations. Low anomalies, corresponding to fewer and/or weaker floods, occurred in 1300–1450, 1590–1680, and two short spells around 1720 and around 1880. The highest levels, corresponding to more and/or stronger floods, occurred around 1480–1525, a short spell around 1700

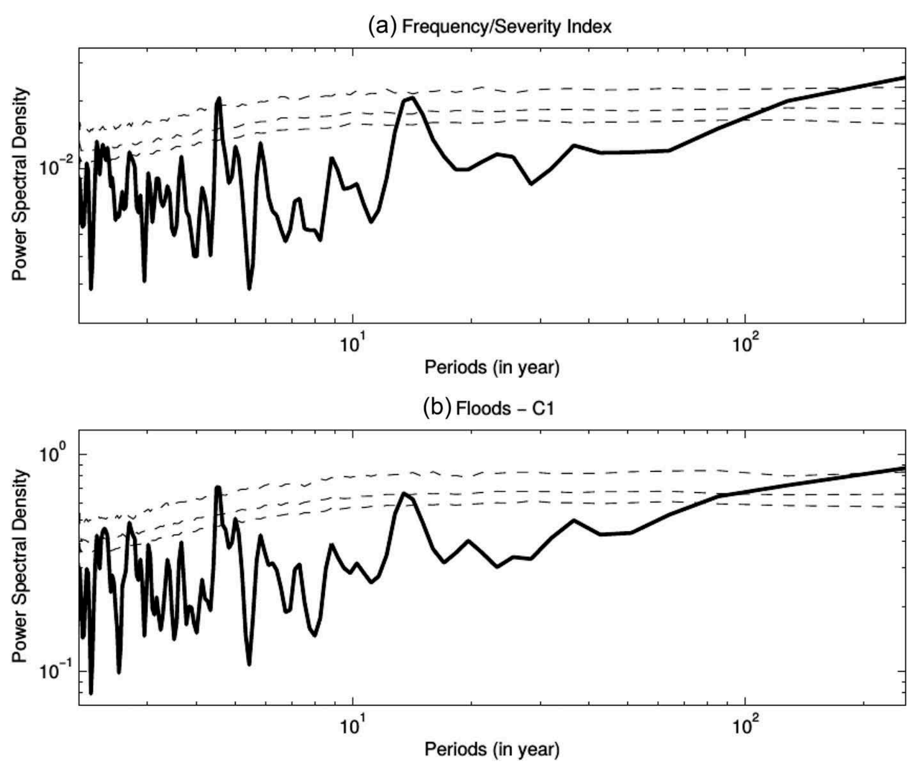


Figure 5. Power spectral density (black line) of standardized anomalies of (a) frequency severity index and (b) all floods minus C1. The thin grey line indicates the one-sided 90%, 95%, and 99% levels of significance according to 5000 red-noise simulations having the same first-order autocorrelation as the flood time series.

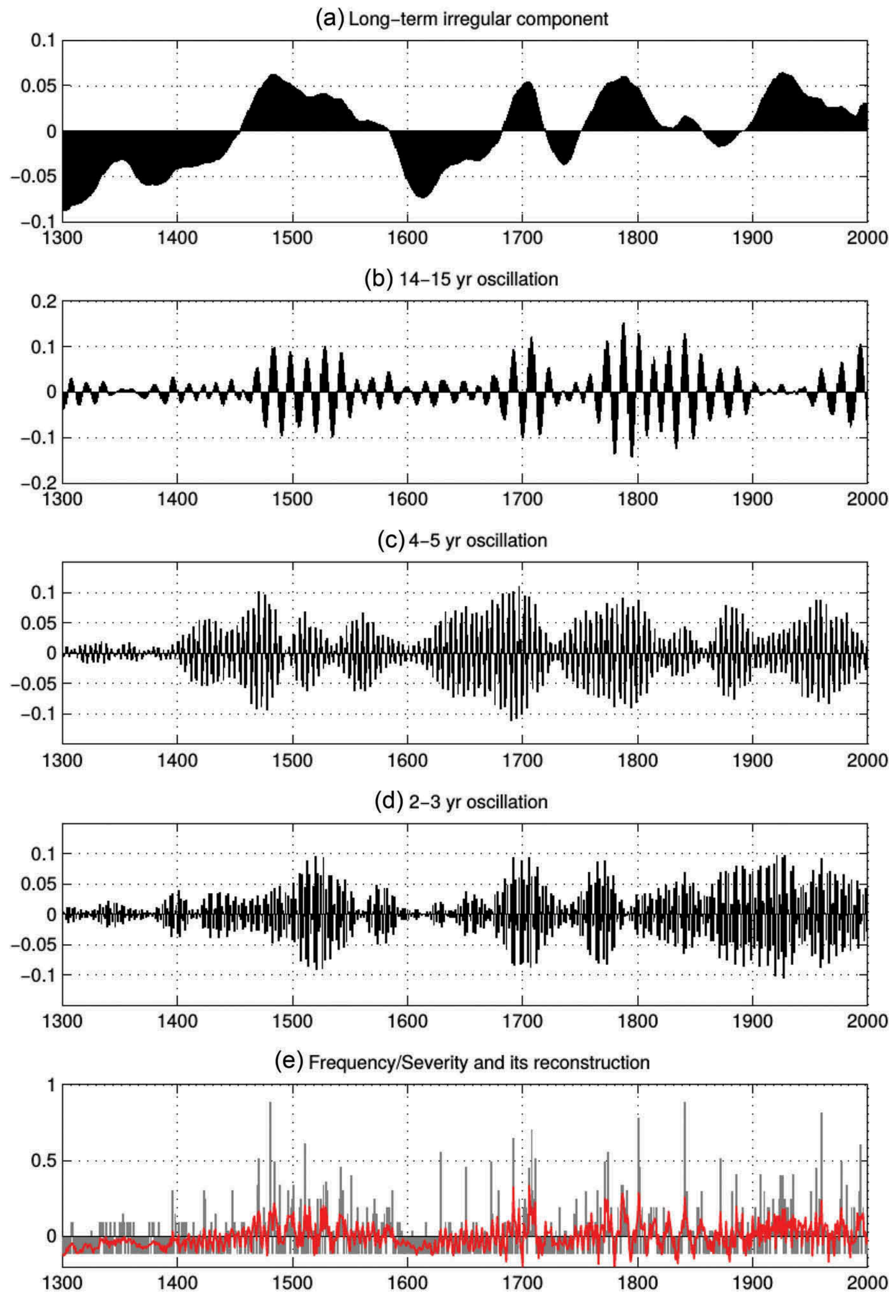


**Figure 6.** (a)–(d) Reconstructed components (RC) from a SSA of frequency severity index (FSI) with a window width of 30 years, corresponding to (a) eigenvector 1, (b) eigenvector 2–3, (c) eigenvector 4–5, (d) eigenvector 8–9, which are significant at the two-sided 90% level according to 1000 Monte Carlo simulations (Allen and Smith 1997). (e) Sum of RCs 1–5 and 8–9 (thick black line) *vs* yearly raw FSI (grey line) expressed as anomalies relative to the long-term mean (1300–2000) FSI.

and 1760–1810, and then during the first half of the 20th century. The 14–15-year oscillation (Fig. 6(d)) is modulated over a longer time scale, with the largest amplitudes usually occurring during high levels of an irregular component. This matching could be due to the positive definite nature of the index and is not necessarily a hydrological/climatic signal. The 4–5-year oscillation (Fig. 6(c)) is also modulated, as well as the 2–3-year one (Fig. 6(d)). The reconstruction using the significant components (red line on Fig. 6(e)) does not reveal the amplitude of the main peaks, but this is rather to be expected due to skewing of the FSI. All computations are re-done on square-rooted FSI to reduce skewing and lead to similar results (not shown).

Figure 7 compares the significant reconstructed components with variations in the height of the Rhone River at Beaucaire. The monthly values of height are first low-pass filtered with a cut-off at 1/600 cycles per month to extract the slowest component,

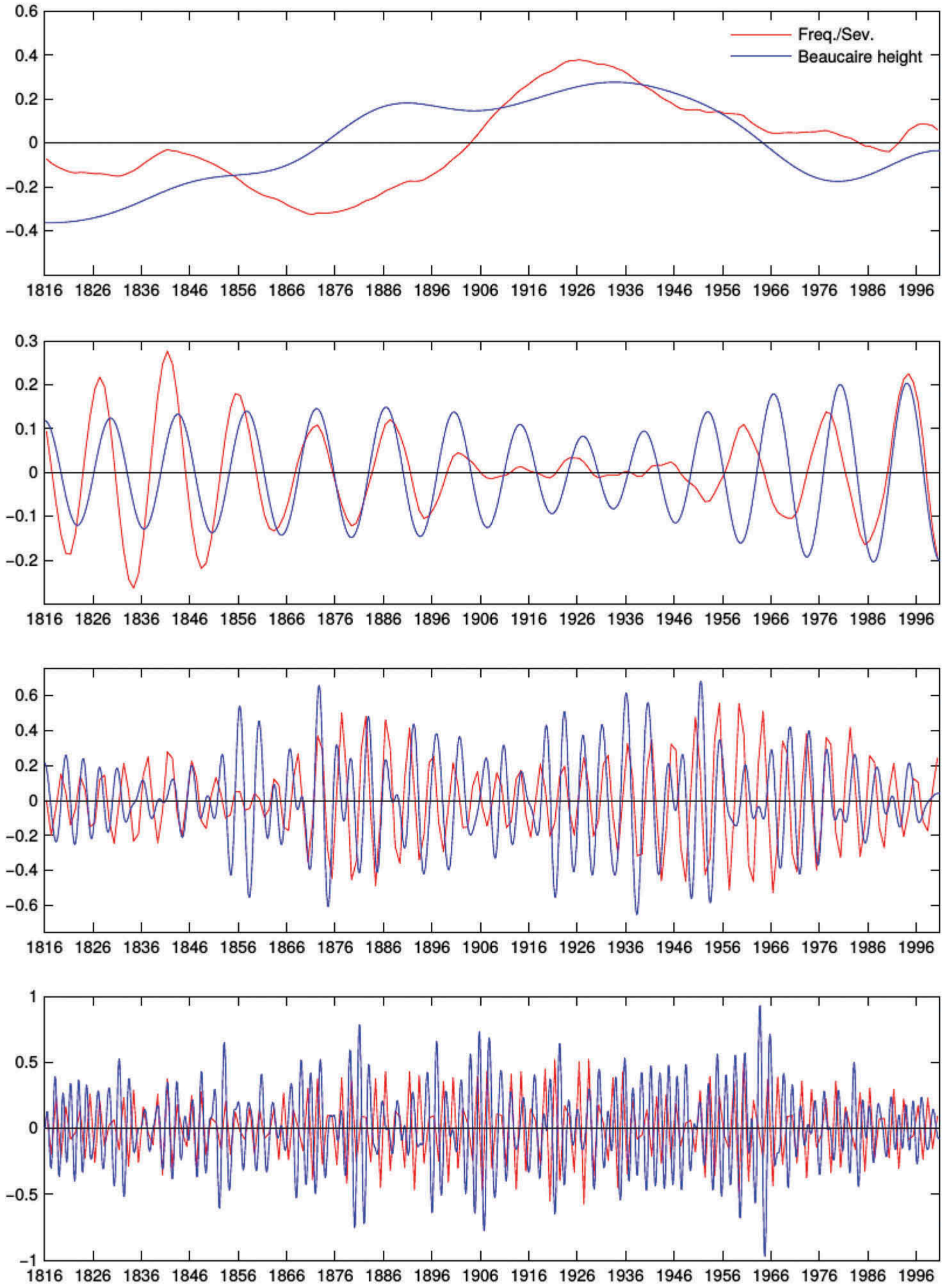


**Figure 7.** Comparison between significant reconstructed components from an SSA of FSI (thick grey line) *vs* the filtered variations of the monthly height of the Rhône River at Beaucaire (thin black line). The variations are scaled so that their standard deviation and mean are equal on 1816–2000. For comparison, reconstructed time series for each component of Beaucaire's height and FSI are scaled so that their long-term means equal zero and variances are identical on the 1816–2000 period.

similar to RC1, then band-pass filtered between 156 and 192 months (14–15-year bandwidth), 36 and 72 months (4–5-year bandwidth) and 18 and 36 months (2–3-year bandwidth) using a recursive Butterworth filter. Figure 7 compares the significant reconstructed components with corresponding low-pass and band-pass variations of the height of the Rhône River at Beaucaire. The slowest variations are not in-phase during the 19th century, because of the destabilization of the riverbed at Beaucaire from 1875 to 1906 (Pichard and Roucaute 2014a, and Section 6.2). In contrast, 14–15-year quasi-oscillations are usually in-phase between the height at Beaucaire and FSI except from 1900 to 1955, when this oscillation vanishes in the FSI (Fig. 7). The 4–5-year and 2–3-year quasi-oscillations show a good correspondence between the height at Beaucaire and FSI, even if the sampling differs between both indices.

## 6 Multifactorial interpretation and discussion of the meteorological factors

The general outline above is based on 517 floods in the southernmost valley of the Rhône River (not including the 445 C1 *crues* or Big Rhône without overflow). To homogenize the data, the FSI was constructed by combining the frequency of the floods with their severity. The discussion below aims to be multicausal for a better understanding of the myriad factors, including climate, which have an impact on the FSI. Consideration of anthropogenic factors is an important issue. Here, we limit ourselves to a characteristic period (15th–16th centuries) that was subject to profound changes. The geometry of the riverbed and the transformations of the channel are also fundamental issues.

### 6.1 Anthropogenic factor vs hydrological consequences

The demographic factor has a strong impact on the deforestation rate and slope erosion, which in turn impact on the speed of surface runoff in the whole catchment. The demographic factor does not act alone, but in synergy with the climate. It is generally accepted that anthropogenic causes (in particular land clearing and deforestation) were worsening effects on the multiplication of torrents and the flooding of the Rhône's tributary rivers (the Durance, Ardèche and Gard) in the Alpine and Mediterranean lands during the LIA. Studies and historical evidence have clearly and abundantly demonstrated this relationship (e.g. Sclafert 1959, Neboit 1991, Pichard 1999, 2006). However, the inter-relationship with climate change remains to be established more firmly.

The rapid increase of floods in the second half of the 15th century (Fig. 4(b)) may be at least partly related to fast population growth after its halving during and after the Great Plague of 1347, when there was a rapid drop in frequency of floods. In Provence, it has been established that the population tripled between 1471 and 1540, by natural increase and by immigration from the Italian Piedmont in the Duchy of Savoy (Baratier 1961). A similar population growth was found in Languedoc (Le Roy Ladurie 1966). There was a revival of villages everywhere, and the creation of new settlements scattered in cleared areas (temporary structures such as *bories*, and permanent ones such as *bastides, mas* and other country dwellings) (Pichard 1999). This was combined with the largest herds and flocks (of sheep, cattle and other livestock) that have ever been recorded. A strong and catastrophic torrential flood erosion was recorded during the late 15th century in Alpine areas, in the Rhône catchment and one of its greatest tributaries, the Durance River (Sclafert 1959).

The speed and scale of changes in the Lower Rhône catchment doubtless had no equivalents until the second half of the 19th century and the 20th century, but with a notable difference – the technical control exercised by man on the channel (building of new dikes) and on the steep banks upstream of this basin (reforestation). A detailed study of this management is a subject in its own right (Bravard and Gaydou 2015).

### 6.2 Geometry of the channel in a period of strong magnitude floods

Today, the Rhône channel can hardly adjust laterally because of embankment. Lateral adjustments of the channel sections are only possible near the mouth of the river, which were subject to large displacements over the past centuries (Caritey 1995). Before its embankment, the active channel of the Rhône River responded to hydro-morphological adjustments that depended on water and sediment fluxes, themselves depending on the ratio between channel hydraulics (discharge, $Q$, and specific stream power, $w$) and sediment supply ($Q_s$) derived from the effects of erosion occurring in the watershed (see the balance of Lane 1955). After this, the channel capacity was adapted to hydrology (dependent on climate) and hydrography (number of branches, channel planform, distance to the coastline), all of which affected the hydraulics of the channel and its overflow capacities in the deltaic plain. During the periods of high magnitude floods that occurred before the phase of channel embankment, the Rhône River showed two possible stages:

(i) a wide, deep and single channel (e.g. the branches of Saint-Ferréol at Le Carrelet and Ulmet at La Capelière in late antiquity; the branch of Grand Passon between 1000 and 1400; see Section 6.3 and Fig. 8(left)); and
(ii) wide, shallow and multiple channels (anabranching; e.g. the Bras de Fer between 1586 and 1712; see Fig. 8(right)).

At inter-annual time scales, one or several high-magnitude/low-frequency floods can change the geometry of the active channel, by enlargement and an increase in the number of channels, and by a decrease in channel depth (i.e. channel infilling by excess alluvial load relative to the channel transport capacity). This phenomenon occurred in the Bras de Fer between 1699 and 1712 (Arnaud-Fassetta and Provansal 1999).

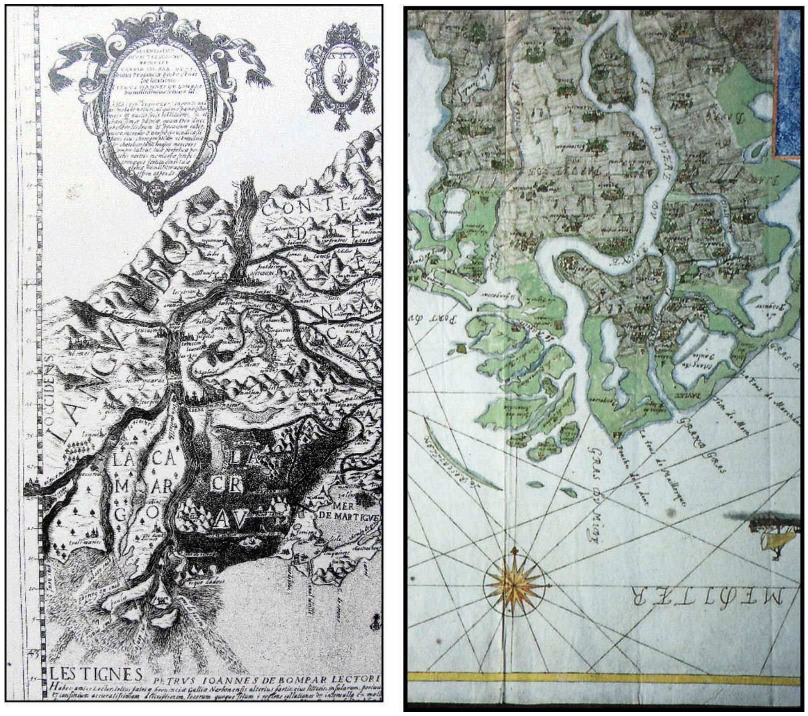


**Figure 8.** (Left) Detail of the earliest map of Provence, by Pierre Jean Bompar (1591, but copied from the lost manuscript map of the humanist protestant Jules Raymond de Solier, before 1586, see Pichard 1993). The image shows the power of the *Passon* branch, pushing out islands and alluvial materials (*Les Tignes*) into the sea. (Right) Detail of a map copied from that of Flour, cartographer (original dated 1635), showing the new, slow, meandering course of the Rhône River (meander *Bras de Fer* in formation) after the avulsion of 1587. Note the important advancement of the delta into the sea. At this time (first half of the 17th century), the east–west maritime currents were stronger than the flow of the Rhône River, as testified by the form of the islands in front of the coastline (*Rascaillan* island). The original map is oriented southwards (here adjusted northwards), (Sources: right, BNF Paris (photo Pichard), and left, Library of Grenoble, France.)

The main reason for this rapid channel change is the grain size of sediment supply. In the Rhône Delta, the alluvial loam, which is essentially composed of sand and silt, is very sensitive to hydrodynamic changes (rapid and abundant deposit of sediment during floods, especially near the mouth because of the low gradient and the blocking effect of the sea).

In summary, the riverbed of the Rhône River did not remain constant throughout the centuries, even if the simple overflow maintained, for the people, a heuristic value through the ages. We are aware of the difficulty of disentangling climatic and geomorphological changes, even if they are possibly correlated factors. Discharge reconstruction work will attempt to isolate the climatic factors of the FSI evolution, a key issue to solve in the future. The overflow occurring during the Late Middle Ages would have been facilitated by the narrowing of the cross-section of the arms and the deltaic mouth. The young humanist writer of Arles, Quiqueran de Beaujeu, argued *ca.* 1530–1540 (Quiqueran de Beaujeu 1614) that the land in the delta (Camargue) is flooded almost every two years, often two years running, and sometimes for three consecutive years. This assertion seems to confirm recent findings that the different deltaic distributaries during the Late Middle Ages were unable to contain an excess of flux water.

Today, the bankfull capacity of both Rhône branches approximates to 8895 $m^2$; in late antiquity, the three distributaries of the Rhône River had a bankfull channel capacity of approximately (8694 $m^2$), very close that of the present day; during the Late Middle Ages, the bankfull channel capacity of the Rhône River was only approx. 3887 $m^2$ (Arnaud-Fassetta 2009). These changes are explained by the variability of the branches and tributaries of the Rhône River in the delta (Camargue) between Arles and the sea (Arnaud-Fassetta 2000, Pichard and Roucaute 2014a). Upstream, the river bed mobility is much less, particularly in crossing of cities.

This example shows that the geometry of the riverbed is one of the factors of change, even if, alone, it cannot explain the great increase of FSI floods during Hyper Phase 1, described above, including climate causes that are to be investigated (Fig. 4(b), and Section 4.2). Other times of discrepancy between flux and bed capacity are discussed below. The branch of the Petit Rhône River grew considerably from the late 17th to the beginning of the 18th century (corresponding to the Late Maunder Minimum). As seen above, it was a period of strong energetic flow. Everywhere in the LRV it was necessary for the inhabitants to decide to leave more space for the river, by moving the dikes back, an operation (*reculat* in the local language) that has left many documentary traces in the late 17th century, particularly in cartography. A third period of discrepancy between the water flux and geometry of the bed occurred in the second half of the 19th century, when the incision of the bed of the main branch (i.e. the Grand Rhône River) in the Rhône Delta was started. This meant that the bed between the banks in Arles was too narrow compared to the abundance of flux. Consequently, there was a big modification of the rating curve of the Arles gauge. A little upstream, the bed at Beaucaire was momentarily destabilized (1875–1906), but quickly regained a more stable state (balance between incision/stock of sediment) in the 20th century.

### 6.3 Characteristic period between two breaks of channel or avulsions, 1587–1711

The power of the Rhône River (flooding and sediment transport) in the 1580s is well illustrated (Fig. 8(left)) by the earliest map of Provence, by Pierre-Jean Bompar (1591, but derived from a lost original in the 1580s, see Pichard 1993). This shows the advancement of the river mouth into the sea due to the formation of numerous islands by the deposition of alluvium, also with Les Tignes, a large sandy *panache* (alluvial materials in midwater) far out to sea (Fig. 8(left)). As a consequence of this instability, in 1587 the river performed an avulsion or lateral moving of its ancient medieval mouth, called *de Passon*, towards a new outlet a little further west. The new mouth was called *Le Bras de Fer* (Fig. 8(right)), the name of a new large deltaic meander reflecting a new fluvial dynamic at work throughout the first half of the 17th century. There followed a period of low intensity of floods with small fluctuations until 1673. At this time the river had to adapt to significant loading of alluvial materials accumulated during the previous period before the avulsion of 1587. In the channel, islands and alluvial accretions of the banks increased. The river and its tributaries (Durance, Gard) meandered between many obstacles. At the main mouth, there was a succession of deltaic outcropping islands that form the maximum historical advance of the delta by progradation or shoreline accretion (Arnaud-Fassetta and Provansal 1999, Pichard *et al.* 2014c, Provansal *et al.* 2015).

Again, in the second half of the 17th century, a return of powerful floods coincided with the ultimate years of the Late Maunder Minimum and culminated in the richest period of floods of the seven-century series and a FSI record. In 1702, 1705 and 1706, the catchments in Provence experienced catastrophic flooding. The Rhône River overflowed repeatedly and broke the harbour banks at Arles 16 times (banks at a height of 6.1 m in the NGF reference) in 1708 alone. As a consequence, in 1711, the mouth of the Grand Rhône River moved a second time, but this time it "jumped" farther southeast, finally abandoning the *Bras de Fer* and taking its present course. Naval engineers and the construction of long dikes helped it to maintain its course. After relocation of the mouth, the fluvial dynamics once again broke down, together with the FSI of flooding from 1712 to 1754, despite some bursts (C3 flood in 1725). However, after the middle of the 18th century, more powerful floods quickly returned. Once again, it is the return of a high-flood period that initiates a new hyper phase with four great fluctuations until 1875 (Fig. 4(b)).

### 6.4 Documentary and instrumental sources for floods and rainfall

Figure 9 shows the annual deviation of the precipitation–drought index (curve), in percentage from the average value (100) between 1500 and 1800. The LRV and French Mediterranean area have long series of instrumental precipitation data. In the centre of Marseille, continuous daily data have been recorded since 1748 and continue today. Homogenization and critical study of this interesting series must be the subject another paper. Other Mediterranean raingauge stations, such as Montpellier (since 1766), Nîmes (since 1745), Avignon (since 1805) and Viviers (since 1776), can give us information on the LRV precipitation regime. Here we want just to compare changes in Mediterranean rainfall (southeastern France) with the evolution of FSI floods between the two ruptures or avulsions described above (Section 6.3). The HISTRHONE database contains much data to document rainfall or drought (Pichard and Roucaute 2014b). We were able to collect 1200 scattered mentions of intense, stormy or continuous rains, prolonged and severe droughts, and also 120 processions *pro pluvia* from the 16th to the 18th centuries. The statistical treatment of this type of data (historical documentary sources) has been attempted in several papers (Martin-Vide and Barriendos Valve 1995, Rodrigo

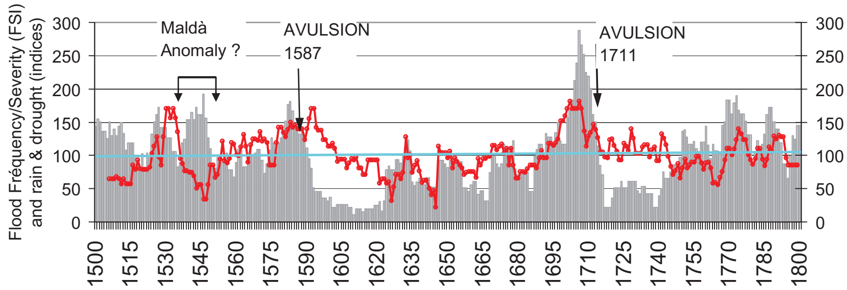


Figure 9. Deviation from the mean (100) of the LRV precipitation–drought smoothed indices (11 years) from the documentary recorded sources in the HISTRHONE database (curve) correlated with smoothed (11-year) FSI of floods (grey bars). The 100 line is the mean of all the rainfall/drought indices. See Appendix.

et al. 1999, Diodato 2007, Rodrigo and Barriendos 2007, Bullòn 2011), as well as methodological remarks in Brazdil *et al.* (2010), and the recent reconstruction in the Czech lands by Dobrovolny *et al.* (2015). In our case, we aim only to compare rainfall/floods in an interesting period of low-intensity flooding between two powerful flooding periods (see also Nicault *et al.* 2008). The methodology of the rainfall indexation is briefly explained in the Appendix.

Finding a visual and apparently good correlation does not exclude a critical interpretation. On the one hand, there are insufficient data for the first quarter of the 16th century; on the other hand, the persistent period of low intensity of FSI floods after 1590 is concordant with a negative deficit trend of rainfall anomaly for a large part of the 17th century. Nevertheless, the rainfall indices remain high for 10 years after the slump in FSI floods, between 1590 and 1600. This indicates the influence of other types of forcing factors that might explain this slump. The same observation applies for the rainfall index after the new slump in FSI after the avulsion of 1711. The period 1712–1753 is also one of rare floods and declining rainfall, which is nevertheless still close to the average. The question of channel avulsion influence on the flow and flood is a tricky problem, especially in the case of avulsion at the mouth. Can it be felt in the channel upstream? We notice that the avulsions in the mouth (in 1587 and 1711) occur at the end of a strong and rich flood phase. The causal link is clear between a strong hydrological phase and avulsion in the channel. These events were followed by periods of hydrological calm. The hypothesis to be confirmed is that a climatic change could explain these successive hydrological phases, and that it is not a channel change that can explain such a turnaround in hydrological regime. A study of several centuries at least could merit highlighting this kind of questioning.

The concordance (Fig. 9) between rainfall and the large or small positive fluctuations in floods is confirmation of the quality of the non-instrumental historical data. Besides, the collection of data can always be improved in the vast Rhône catchment. Yet, a contradictory period remains to be explained. Before, during and after 1540, a severe drought raged in the LRV, as it did in Europe (Wetter *et al.* 2014); however, this was a period of powerful fluctuation in flood frequency. Such an abnormal case has already been investigated, but in Catalonia between 1760 and 1800: "*The Maldá anomaly can be defined as a lengthy period of time in which the inherent characteristics of the Mediterranean climate became accentuated and showed a simultaneous frequency of droughts and floods not experienced with such frequency in the last 500 years, at least not in Catalonia*" (Barriendos and Llasat 2003). (Maldá was the contemporary author of a testimony that described this phenomenon and the concept comes from his name.) Heavy and sudden rainfalls during prolonged droughts are in fact inherent in the Mediterranean climate, but a close examination of these extraordinary years in the 1540s in the LRV remains to be done. Is this comparable with the case in Catalonia, or is it due to inadequacy or lack of documentation?

### *6.5 The lowest water levels and periods when the LRV nearly dried up*

The most serious phenomena of low flow and almost total lack of water occurred during the LIA. In 1639, the Petit Rhône River could be forded at its fork at the head of the delta. Figure 10 shows the dates and distribution of some of the lowest waters in the deltaic course of the Rhône River, distinguished by their severity, duration and grouping over successive years. In the Mediterranean climate, excessive isolated low levels may occur during a phase rich in overflows, but a succession of years with low water levels can also be a symptom of climate fluctuation. Out of a total of 114 lowest waters, 93 occurred between the 15th and 19th

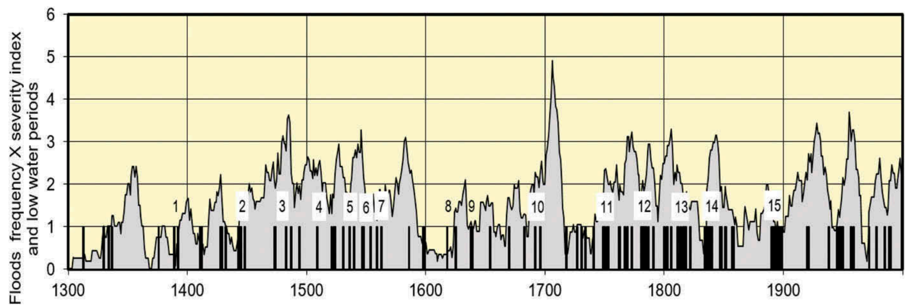


**Figure 10.** Periods of lowest water (bars) with cumulated annual FSI flood curves (11-year running average).

centuries. The main decadal peaks of FSI are poor in low waters (as in 1346–1367, 1395–1406, 1574–1591, 1696–1715 and 1921–1934). Four groups of successive years of low waters are an objective sign of drought fluctuation: 1781–1785 (11 on Fig. 10), 1816–1818 (12) and, above all, 1834–1840 (14) when navigation was impossible for months, and the entire decade 1890–1899 (15), a time of riverbed destabilization, before the appearance of new flow conditions and riverbed stability in the 20th century (Pichard and Roucaute 2014a, in particular their Figs 63 and 65).

In 1337, the Rhône near Arles was already low. In 1389 (1) it was so low that swamp water flowed consistently. In 1448 (2) the salt ships could not get up the river to Avignon. In 1483 and 1487 (3) the waters were the lowest ever known. In 1492 and 1509 (4) the mills on the river could no longer function for lack of water. From 1536 to 1563 several low waters (1536, 1540, 1547, 1559 and 1563) (6 and 7)) made it possible to ford the river or work in the river bed. In 1618 (8) the low waters revealed the piers of an ancient bridge (Roman?) at the fork of the Petit Rhône River. In 1639 (9), the lowest level known today, before the bed incision described in Section 6.2, was measured in Arles (1.1 m above zero in the NGF reference). In 1692 (10) Roman lead pipes were discovered at the bottom of the river due to the fall in the water level. Other artefacts were discovered for the same reason in 1818, 1819 and 1822 (13). In 1802 and 1812 carts could cross the river at Fourques (Petit Rhône River). From 1827 to 1858 the waters were the most consistently low of the entire series. Sequences of years of drought occurred in the 1730s (11) and the 1780s (12) when the water was low. Likewise, drought occurred over long periods of time in the 1830s, and navigation was not possible (14). The late 19th century (1890–1899) was a period of weaker hydrology (15). Throughout 1921, the waters were consistently low. For evidence, refer to the HISTRHONE database, Ressources/ Synthèses/Chronologie des sécheresses (chronology of droughts), or Ressources/Recherche par type d'événements (search for type of event).

### 6.6 The LIA and floods in the context of the Mediterranean lowlands

Over 20 overflows and floods are explained by the mechanical effect of huge amounts of ice accumulated in the river branch to Avignon, or in the straight channel of the Rhône River at Arles. Worse still, ice encumbered the mouth of the river and the marine shoreline. Moreover, there is a question as to the relationship between flood frequency and the 201 episodes of river ice (Fig. 11). The beginnings of the LIA in the 14th–15th centuries were accompanied by 14 important but isolated episodes of ice blockage. After a long

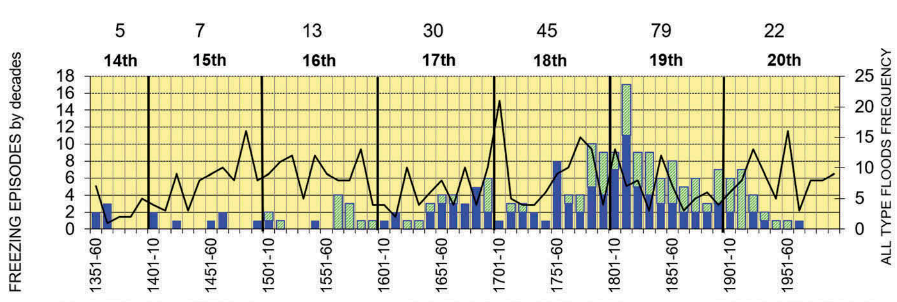


**Figure 11.** Complete freezing of the LRV and episodes of floating river ice. Comparison is made with overall flood frequency (black curve). Arabic numerals refer to the number of freezing and floating ice episodes per century. The raw material is detailed in the *chronologie des glaces* (chronology of ice periods) in HISTRHONE under "Resources"/"Syntheses".

remission from 1507 to 1563, these episodes returned when the river deployed all its force with repeated flooding. During the late 16th century, the floating ice become more frequent. The first half of the 17th century was a time of lesser activity of the river after the avulsion in 1587. The slower-moving river developed its channel, banks and much more complex mouth. Ice blocking was scarce and the passage of floating ice was still observed, but ice episodes occurred in much greater numbers in the second half of the century, with 22 severe episodes (blocking or floating ice) occurring in the winters between 1650 and 1700, in comparison with only eight from 1600 to 1650. So there is a strong contrast between the reduced river dynamics and ice after the avulsion of 1711 (10 episodes) and the 100 years between 1751 and 1850 (85 episodes), the true climax of the LIA, as shown by the ice in the Rhône River, but also by the FSI. Despite a downward trend after 1850, floating and blocking ice remained frequent, including at the beginning of the 1890s, a cold LIA time in the LRV. Ice occurred frequently over two decades at the beginning of the 20th century, but global warming gradually made these events more rare after 1920. The last severe ice event occurred during the cold winter of 1963.

### 6.7 Seasonal variability of floods by half-century: a significant evolution?

The seasonal topic of floods cannot be ignored. Analysis over many centuries is of great interest. Figure 12 shows a strong variability in the seasonal distribution of the floods, In the Late Middle Ages, spring (March–April–May, MAM) and autumn (September–October–November, SON) seasons, FSI floods were almost equal. In the 15th century, flooding was more prevalent in the warm seasons, spring and summer. The development of the winter (December–January–February, DJF) and summer (June–July–August, JJA) floods characterizes the classical LIA cold period: late 16th century and 18th and 19th centuries. The rare floods of the 17th century were concentrated (79%) in the second half-year, between July and December. The regime of floods in the 20th century, predominantly in the autumn, cannot be extrapolated in the history of flooding since the Middle Ages. Inter-seasonal flood variability is much more than a marginal phenomenon.

## 7 Conclusions

### 7.1 Overview

The construction of a detailed historical database (HISTRHONE) allowed an important reconstruction of the long history of floods in the Lower Rhône Valley from Orange to the delta and the sea. A total of 1542 documentary sources were used, besides a few hundred thousand instrumental observations of daily fluvial heights at Beaucaire and Arles and other stations, from 1816 to 2000.

We focused on three categories of floods of increasing severity (C2, C3 C4). The frequency was combined with severity into a single index (FSI). Indices were then smoothed by 11- and 31-year running means highlighting many fluctuations (three to four per century) and two low-flooding periods, between 1590 and 1680 and the last quarter of the 19th century, the first one including three smaller fluctuations between two changes of course of the principal mouth (avulsion), in 1586 and 1711. This characteristic period was examined in detail and compared with a reconstruction of a rainfall drought index (1500–1790). The two avulsions

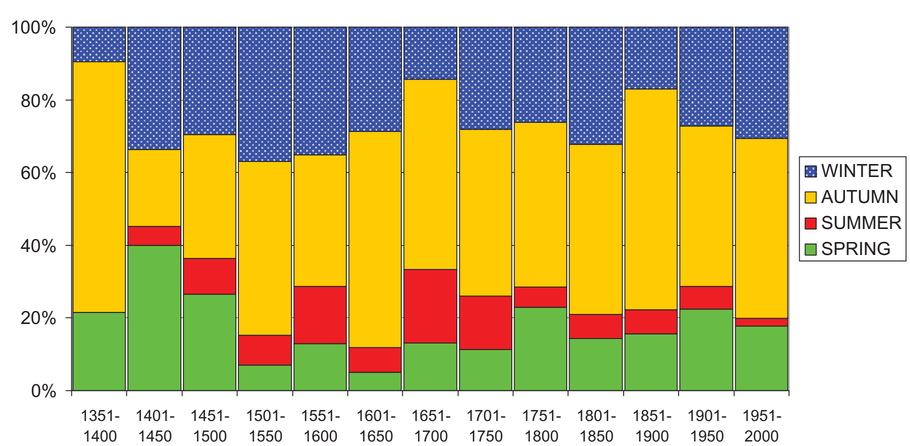


Figure 12. Percentage of FSI flood distribution per half-century by season: winter (DJF), spring (MAM), summer (JJA) and autumn (SON), taking into account the C2, C3 and C4 floods.

occurred after a wet period of strong hydrological dynamism. Short quasi-periodic oscillations occurred every 2–3 and 4–5 years, when C2 and C3 floods, respectively, returned. The catastrophic C4 floods increased greatly in frequency in the second part of the modern ages and in the contemporary world (nine between 1301 and 1650 and 27 between 1651 and 2000). The opposite is found for the C3 floods of moderate severity (85 and 59 for the same periods, respectively). If anthropogenic influence is a crucial point throughout, here we have only touched on a period of intense demographic growth and topographic upheaval (1470–1550), after the severe depression after the Black Death (1347). This period was one of the richest in flood frequency, but not in severity. The reduced capacity of the riverbed and deltaic distributaries explain this frequency and the ease of overflow only in part, mainly at the delta.

The low FSI of floods in the 17th century (1590–1680), occurred between two long secular fluctuations,1480–1590 and 1690–1875, including several successive FSI flood-rich periods. For ease of description, we named them Hyper Phase 1 and Hyper Phase 2. It remains unclear if it is possible to describe the FSI of floods in the 20th century in this way, after a new period of low flood frequency from 1875 to 1906. These two periods of poor flood frequency were also characterized by major rearrangements or destabilization of the riverbed and the river mouth, either naturally or by human intervention, the latter mostly after 1875.

The so-called flood hyper phases 1 and 2 accompany the upward trend and culmination in winter frequency/severity, shown by the freezing of the river and passage of floating ice (167 episodes between the late 16th century and late 19th century). That is the most eloquent testimony of the LIA in a low Mediterranean valley. In the same way, increasing and recurrent episodes of considerable lowering of the Rhône River level arose (fording of the Petit Rhône River). The question of the linked or related frequency of floods, ice and extreme low water is an issue for future research and climate explanation, insofar as a common cause might be found.

### 7.2 The LRV compared to other European river floods

The LRV is predominantly marked by a Mediterranean climate (Pardé 1925), but the genesis of its floods is complex and the 19th–20th centuries regime described by Pardé could have been different in earlier ages, as evidenced by seasonal variability, clearly indicated from the 14th century (Fig. 12). This analysis is not the subject of this paper, but the comparison with studies of other rivers is only a first step in this direction. Here, we follow the comprehensive study with maps pursued by Schmocker-Fackel and Naef (2010). Mediterranean influences are, however, different in Catalonia, which is subject to convective local rainfall episodes in autumn and synoptic phenomena in late summer and early autumn (Barrera-Escoda and Llasat 2015). In the French Mediterranean region, we distinguish from Pardé (1925) the Cevenol episodes causing "flash floods" on the Rhône River, and the much worse extensive Mediterranean episodes, extending to the northwestern Alps or even beyond the Alps into the Upper Po Valley. The great Alpine tributaries (Isère, Durance) are themselves affected by different influences, Mediterranean and/or oceanic. The Saône River, influenced by oceanic depressions, exerts a formidable influence from Lyon to Avignon with the input of the Jura mountain waters. Mediterranean and oceanic rainfalls together create the most catastrophic "general floods" from Lyon to the sea, as occurred on 1 November 1840 (Pardé 1925, Pichard and Roucaute 2014a).

This brief summary of the different influences could explain a large part the concordance and non-concordance with other neighbouring or distant catchments, but from 1300 to 1500 there are few relevant comparative data in Europe (Table 5).

The comparative study summarized by Table 5 highlights a better concordance between the greater rivers rather than the small and medium rivers, which are more affected by local and convective phenomena. The precise dating of the positive or negative oscillations (rich- or poor-frequency flood periods) is the principal requisite for improving the detection of the atmospheric factors from a synoptic analysis.

Comparison of the third rich-flooding period (1690–1711) with that of the other rivers brings out the uniqueness of this gigantic fluctuation, unmatched elsewhere (Fig. 9). Besides the abundant evidence contained in the HISTRHONE database (annual transcription of the records), an independent paper has recently highlighted the singularity of the same years, in a study of the sediment deposited by the Upper Rhône floods in Lake Bourget: "*The four highest volumes of the last 350 years were deposited during the early 1700s, in A.D. 1686, 1711, 1733 and 1737…The highest volume of terrigenous sediments was brought by the A.D. 1711 event (182 x $10^3$ $m^3$) equivalent to more than twice the volume brought by the second intense most event (81 x $10^3$ $m^3$ in A.D. 1733)*" (Jenny *et al.* 2014). The year 1711 was also when the second change of mouths

**Table 5.** Frequency of rich and poor floods in the LRV and comparison with the long documentary and instrumental flood series for the Mediterranean, and Northern and Central Europe. Abbreviations: Cat.: Catalonia and Mediterranean coastal area of Spain (Barriendos and Martin-Vide 1998, Llasat *et al.* 2005); Sp.: Spain (Benito *et al.* 2001, 2003); It.: Italy (Camuffo and Enzi 1996, Zanchettin *et al.* 2008); Ger.: Germany (Glaser 1998, Böhm and Wetzel 2006); Cz.: Czech Republic (Brazdil *et al.* 2014); Neth.: The Netherlands (Glaser and Stangl 2003); Swi.: Switzerland (Schmocker-Fackel and Naef 2010). Grey shading refers to strong divergent evolution compared to the LRV.

| Flood-rich periods (LRV) | Rare or medium flood periods (LRV) | Mediterranean catchments | Northern and Central Europe catchments |
|---|---|---|---|
| 1. 1328–1359: FSI peak in 1353 (FSI = 7.23) | | Cat. Segre (Lleida) and Ter (Girona) basins: flood-rich period | |
| | 1. 1360–1445: alternating low or moderate FSI floods | Cat. Ter, Llobregat and Segre basins: low and moderate flood frequency | Ger. Isar River (Munich); flood-rich period |
| 2. 1452–1589: flood-rich Hyper Phase 1 FSI peak in 1481 (FSI = 13.08) and high frequency of floods from 1578 to 1587<br>Five apparent rich fluctuations (11-year running average) with peaks in 1483, 1501, 1526, 1546 and 1583 | | Cat. No equivalent except in the Segre basin: 15th, late 16th and early 17th centuries, the richest flood period (see below). 1570–1630: positive oscillations in the Mediterranean coastal area of Spain: 1579–1596, 1600–1613 and 1617–1632.<br>Sp. Central Tagus basin: flood-rich period with late 16th century frequency peak | Ger. Main, Pegnitz: flood-rich period only in mid-16th century; Middle Elbe River: flood-rich period in late 16th century<br>Lech and especially Isar, 1470–1500: flood-rich period; medium or poor afterwards<br>Swi. Late 16th century (1560–1590): flood-rich period<br>It. Po River, late 16th century: flood-rich period |
| | 2.1596–1690: moderate or rare flood period<br>1596–1623: rare floods<br>1624–1690: medium flood frequency (FSI); moderate fluctuations with annual peaks in 1629 (FSI = 8.77), 1651 (FSI = 7.5) and 1673 (FSI = 8.0) | Cat. Three periods:<br>1.1600–*ca.* 1630: continuation and record peak of the flood-rich period of the late 16th century<br>2. *ca.* 1630–*ca.* 1650: flood-poor<br>3. *ca.* 1650–*ca.* 1690: medium flood fluctuations<br>It. Tiber River: flood-rich period<br>Po River: medium flood frequency | |
| 3.1690–1711: highest FSI, record number of the series<br>1300–2000: main FSI peaks in 1692 (FSI = 10.0) and 1711 (FSI = 9.23) in a period of high frequency of floods (see the comments at the end of the Conclusion section) | | Cat. Flood-poor period in all catchments studied except a little fluctuation for the Llobregat River<br>It. Po River: medium flood frequency<br>Tiber River: poor flood frequency | Ger. Flood-poor period for Lech (Augsburg), Isar (Munich), Weser, Main<br>Neth. Medium flood frequency in the Lower Rhine Delta<br>Cz. Morava River, 1690–1699: high flood frequency; 1701–1710: low flood frequency but "under-estimated" (Brazdil *et al.* 2014) |
| | 3. 1712–1753: flood-poor (FSI) period | Cat. Low flood frequency | Ger. Lech and Isar: medium frequency floods<br>Rhine: medium frequency<br>Cz. Morava: medium frequency floods |
| 4. 1755–1860: flood-rich Hyper Phase 2 with increasing FSI annual peaks: 1755 (7.46), 1774 (8.77), 1801 (9.0), 1802 (11.3), 1841 (13.1)<br>Five apparent fluctuations (11-year running average) with peaks in 1760, 1773, 1787, 1806, 1843. Short rare flood and drought period 1826–1835 | | Good correspondence of flood-rich periods:<br>Cat. 1750–1790: flood-rich period<br>*ca.*1835–*ca.*1870: another flood-rich period | Swi. 1740–1790: flood-rich period |
| | 4. 1875–1906: low and medium FSI flood period despite two significant flood events: 1882 and 1886 | Cat. Late 19th century low flood frequency<br>Sp. Tagus River: Growing frequency of floods, late in the 19th century | Ger. Main and Lower Rhine valleys (Neth.): rare and poor flood frequency<br>Pegnitz: medium flood frequency<br>Lech (Augsburg): low flood frequency<br>Isa (Munich): high flood frequency |

(*Continued*)

**Table 5.** (Continued).

| Flood-rich periods (LRV) | Rare or medium flood periods (LRV) | Mediterranean catchments | Northern and Central Europe catchments |
|---|---|---|---|
| 5. 1907–1970: return of high FSI floods in the 1920s, 1930s and 1950s Three apparent fluctuations (11-year running average) culminating in 1928, 1947 and 1959 | | Cat. Poor flood frequency Sp. Tagus RIver: Extreme rich-flood frequency (but oceanic influenced regime) | Ger. Lech: medium frequency flood period in Augsburg Isar: flood-rich period at Munich Neth. Lower Rhine: high flood frequency |
| | 5. 1970–1990: medium or rare FSI floods; final management of the LRV by the CNR society | | |
| 6. 1991–2000 onward: increased FSI flood due to the return of extreme severity floods 1993, 1994 … 2003 | | | |

(avulsion) was triggered in the delta of the Lower Rhône River (Fig. 8) and the maximum "progradation" (shoreline migration by accretion) of this new mouth occurred.

The precise description of a long flood series in a limited area of a great river, the Lower Mediterranean Rhône, and its situation in the European environment, should be a good and robust foundation for a future synoptic and atmospheric study as exemplified by earlier papers (Glaser *et al.* 2010).

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## Disclosure statement

No potential conflict of interest was reported by the authors.

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## Appendix

**Method of reduction in indices of the documentary rainfall/drought sources**

Before the development of instrumental sources of rainfall statistics, a rich corpus of historical or narrative data was widely dispersed in a large variety of sources: personal and public records, journals, letters and the first regular observations of weather. From the HISTRHONE database we were able to gather 1200 occurrences of heavy or recurrent precipitation, storms, 120 rogations *pro pluvia* (see methodological remarks of Martin-Vide and Barriendos-Valve 1995), and mentions of physical phenomena of drought, from 1500 to 1790. This collection of data must be considered as a first stage in the building of a specialized database of the distribution of extreme precipitation. Nevertheless, the correlation with independent instrumental data (1745–1790) is representative (Fig. A1). The methodology was as follows:

(1) The narrative precipitation/drought data were arranged in a matrix by months and years. These data become significant from 1525–1530, and their volume doubles in the 18th century compared to previous centuries (instrumental data are not included).
(2) An index was assigned to every episode or sequence – recurrent or heavy rains: 2; storms: 1 or 2 according their spatial extent; extreme torrential rain in an entire region: 5; one procession *pro pluvia*: −1; one month or several weeks without rain: −1 (cumulative negative indices if several months of drought arose); and severe drought including exceptional low water flow: −5.
(3) Indices were added up by year and turned into synthetic annual precipitation–drought indices.
(4) Synthetic indices were distributed according the standard 7-degree scale from +3 (extreme wet index) to −3 (extreme drought), with zero (0) the average value of the series.
(5) Annual values were smoothed by 11-year moving average (as for the floods).
(6) Finally, the smoothed values were calculated as deviations from the mean (100).

Correlation between indices calculated from the only narrative rainfall records in Provence, especially in the LRV, and independent measured precipitation data for a single location, Marseille (1750–1790), confirm that the documentary historical data ($R^2$ = 0.52) may well give an accurate picture (Fig. A1).

The purpose of this approach is limited. Intentionally, we dismissed a calibration from the instrumental data of the 20th century. Our experiment was a simple verification with the contemporary measured rainfalls from 1748 to 1790. Other approaches must homogenize documentary and instrumental data in a long series from 1500 to date, as in the recent paper of Dobrovolny *et al.* (2015).

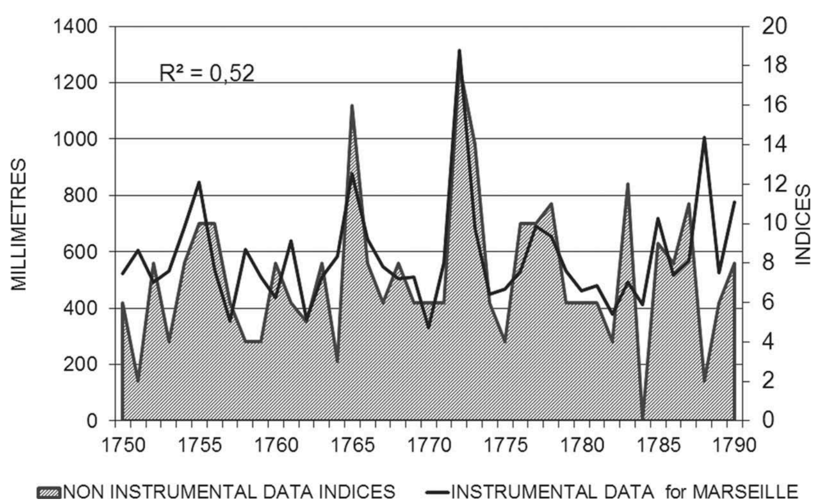


Figure A1. Comparison between measured rainfall in Marseille and the rain and drought indices from documentary sources in southeast France (1750–1790).