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Classification of the flood severity of the Guadalquivir River in the Southwest of the Iberian Peninsula during the 13th to 19th centuries

Leoncio GARCÍA-BARRÓN[1], Mónica AGUILAR-ALBA[2], Julia MORALES[3], Arturo SOUSA[3*]

[1]*Department of Applied Physics II, Universidad de Sevilla, E-41012 Seville, Spain*

[2]*Department of Physical Geography and AGR, Universidad de Sevilla, E-41004 Seville, Spain*

[3]*Department of Plant Biology and Ecology, Universidad de Sevilla, E-41012 Seville, Spain*

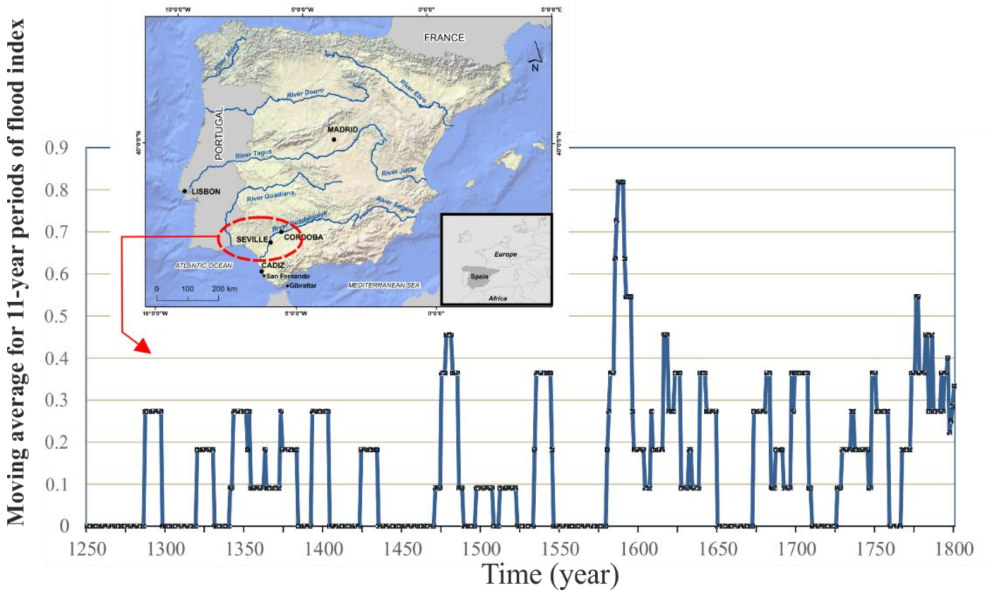
**Corresponding author*: asousa@us.es

Floods of the Guadalquivir River from the 13th to the 19th century

HIGHLIGHTS

- We study the Guadalquivir River floods in Seville from the 13th to the 19th century.
- For this study, the available documentary records from historical records were used.
- An annual severity index flood was developed based on flood impacts.
- Of the ten most destructive floods, five occurred between 1598 and 1701 AD.
- The results obtained contribute to multiple-century knowledge of historical floods.

GRAPHICAL ABSTRACT



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[1]*Department of Applied Physics II, Universidad de Sevilla, E-41012 Seville, Spain*

[2]*Department of Physical Geography and AGR, Universidad de Sevilla, E-41004 Seville, Spain*

[3]*Department of Plant Biology and Ecology, Universidad de Sevilla, E-41012 Seville, Spain*

**Corresponding author*: asousa@us.es

ABSTRACT

This study estimates the flood severity between the 13th and 19th centuries on the southwestern Iberian Peninsula based on the historic records of the impacts of the Guadalquivir River flooding on the city of Seville (Spain). The main documentary source was "Critical history of the floods of the Guadalquivir in Seville" (1878), which compiles news from different observers, who were contemporaries of each flood. Regarding the methodology, it was necessary to transfer the information from different documentary sources to ordinal indices, which required developing allocation criteria per flood impact. From the annual severity index assigned to the different floods, an interannual series was generated. Through interannual weighing of the flooding indices, it was possible to deduce the durations and intensities of sequences of flood periods between 1250 and 1850. Of the ten floods classified as most destructive during the five centuries analysed, i.e., from 1280 to 1880, five occurred during little more than a century (1598-1701). The obtained results contribute to knowledge on regional rainfall, as well as to historical climatology and hydrology, over multiple centuries.

Keywords: floods, Guadalquivir River, documentary sources, historical climatology.

RESUMEN

Este estudio estima la severidad de las inundaciones durante los siglos XIII a XIX en el suroeste de la Península Ibérica. Para ello nos basamos en las crónicas históricas de los impactos provocados por las inundaciones del río Guadalquivir en la ciudad de Sevilla (España). La principal fuente documental es "Historia crítica de las riadas en Sevilla" (1878) que recopila noticias de distintos

observadores contemporáneos de cada inundación. Por ello, desde el punto de vista metodológico, ha sido necesario transferir la información procedente de fuentes documentales variadas a índices ordinales, para hacerlas comparables. Esto implica elaborar criterios de asignación por los impactos de las diferentes inundaciones. A partir del índice anual de severidad asignado a cada inundación, se genera la serie interanual. Mediante la ponderación interanual de los índices de inundación se deduce la duración e intensidad de las secuencias de periodos de inundación desde 1250 hasta 1850. De las diez inundaciones clasificadas como más destructivas en los cinco siglos estudiados, desde 1280 a 1880, cinco de ellas se concentran en poco más de un siglo, entre 1598 a 1701. Los resultados obtenidos contribuyen al conocimiento multisecular de la pluviometría regional y es una nueva aportación a la climatología e hidrología histórica.

1. Introduction

Knowledge on the evolution of climate over past centuries, before instrumental records, is based on multiple sources that provide information directly or indirectly, i.e., proxy data. Historical, botanical, and geological evidence are worth sources of flood information. Wilhelm et al. (2019) show the historical development of the different methodological approaches and the type of information that these files provide. Fundamentally, there are two types of proxy data: natural and documentary data. This study is exclusively focused on proxy data from documentary sources. One of the frequently used types of documentary proxy data is ecclesial documents related to tithe and rogation ceremonies. A tithe payment, i.e., an economic tax of one tenth of a harvest, shows the annual agricultural production associated with meteorological factors, although it is not always easy to interpret. Moreover, in the face of meteorological adversity, the Catholic Church regulated liturgical celebrations of intercession: pro pluvia rogations, in the case of prolonged droughts, or pro-serenitate rogations, in the case of persistent rainfall with floods (Martín-Vide and Barriendos, 1995; Tejedor et al., 2019). The advantage of the rogation method is that it maintained the spatial and temporal uniformity of the applicable type of ceremony, which indicates the severity attributed to each event (Cremades, 2017).

Other relevant documentary sources of historic climatology are the records and annals of historians who included unique meteorological circumstances in their stories (Rodrigo et al., 2012), minutes of local corporations and institutions that gathered information on exceptional situations such as droughts or floods (Barriendos et al., 2019), and reports of trustees of noble houses about the economic results of agriculture that they considered to be affected by meteorological conditions (Fernández-Fernández et al., 2014). This information is frequently scattered and must be filtered from the main focus of the set of consulted documents. In general, literary information on climatic phenomena is linked to the subjectivity and inaccuracy of the chroniclers and may be influenced by external factors. To develop temporal series from this information, it is necessary to establish ordinal levels of intensity that allow the creation of quantifiable scales (Pfister et al., 1999).

Different authors with varied orientations have investigated historical floods in Europe (Brázdil et al., 2006; Glaser et al., 2010; Kjeldsen et al., 2014; Benito et al., 2015; Blöschl et al., 2020), as well as their frequency and intensity in the main Spanish drainage basins (Benito, et al., 2003; Machado et al., 2011; Fragoso et al., 2015; Balasch et al., 2019). Regarding the floods of the

Guadalquivir River, the geomorphological studies of Uribelarrea and Benito (2008) and Baena et al. (2019) are worthy to mention. Despite the large number of historical documents on the Guadalquivir River floods, according to Zamora (2014) the impacts of these floods have not been addressed thoroughly, unlike other European rivers, except Borja Palomo's compilation. Among the studies focusing on the historic climate of the southern Iberian Peninsula, it is worth highlighting studies on South Portugal (Alcoforado et al., 2000; Do Ó and Roxo, 2008), the Doñana wetlands (Sousa et al., 2010), Southern Extremadura and Andalusia (Rodrigo et al., 1999; 2012; Barriendos, 2007; Rodrigo, 2007, 2017, 2018).

Barriendos and Rodrigo (2006) compared historic floods of the main Spanish drainage basins. According to these authors, it is possible to differentiate the typology between the Atlantic and Mediterranean watersheds, although the drainage basin is the adequate reference unit for the analysis of the chronology of floods. Thus, the Guadalquivir basin, in the South Atlantic side of the Iberian Peninsula, only experienced synchronous catastrophic floods with the Segura basin in 1778 A.D. and with the Douro basin in 1545 A.D (Fig. 1). García-Codrón (2004) stated that in the Iberian Peninsula, the highest seasonal risk of flooding appears in spring for the central plateau under Atlantic influence (Douro, Tagus and Guadiana), during autumn for the Mediterranean watershed (Jucar and Segura), and in winter for the Guadalquivir basin. Therefore, this information highlights the need to conduct historical climatological studies that are thoroughly focused on the main basins, such as the Guadalquivir basin object of this study.

In southern Spain, it is possible to distinguish two causes of flooding:

a) Persistent rainfall due to a long and continuous period of precipitation (or melting) in Atlantic basins, as the Guadalquivir basin. These are more frequent in winter.

b) Torrential rains caused by periods of very intense and short rains. These are frequent in Mediterranean basins as a consequence of cold drops, with greater probability in the months of autumn.

In the Guadalquivir river basin, although floods can be caused by brief torrential rainfall, they are generally influenced by prolonged and persistent rains, with subsequent runoff from an upper river basin.

The risk of flooding in the Guadalquivir basin is essentially influenced by pluviometric and orographic factors. With respect to the former, it is worth highlighting an important irregularity in precipitation at both the seasonal and interannual scales, with a high frequency of intense rainfall in wide areas of the basin. The annual precipitation average for the entire watershed is of 640 mm. This, however, hides very relevant variations, with over 1,000 mm/year in some areas compared to other areas with only 300 mm/year (García-Barrón et al., 2011). This is mainly due to frontal precipitation that responds to the entry of Atlantic storms through the Gulf of Cadiz (Vallejo, 2000).

Flooding in the lower Guadalquivir River basin has a high flow rate, which is surprising, given the slight slope in that region and the deceleration exerted by the sinuosities of its course (García Martínez, 2003). As stated by Vanney (1970), this scenario is due to the acceleration caused by the local volume contributions.

The aim of this work is to classify the floods of the Guadalquivir River on the city of Seville from the 13th to the 19th century using historical records gathered by Borja Palomo (1878).

2. Study area and data

The following sections describe the urban circumstances of the city and its relationship with the river to better understand the subsequent categorisation of the impacts caused by the floods of the Guadalquivir River on the city of Seville. Most of the studies that analyse the floods of the Guadalquivir focus on the effects on the urban transformation of Seville and on hydraulic works during the 19th and 20th centuries (Del Moral, 1991; 1992). On the other hand, studies of the floods of the previous centuries are very scarce. We analyse the main source of documentary proxy data used in this study (Borja Palomo, 1878) that were subsequently compared with instrumental meteorological data.

2.1. Study area. The city of Seville and its relationship with the floods of the Guadalquivir River

The Guadalquivir River is the most important river on the southern part of the Iberian Peninsula (657 km long). It crosses Cordoba and Seville (Fig. 1) and discharges in Sanlúcar de Barrameda, next to Doñana National Park. Guadalquivir River is situated in the southwest of Spain, where there is a Mediterranean climate that is influenced by the Atlantic Ocean (García-Barrón et al., 2013).

Figure 1 around here

The city of Seville (37.38°N; 5.97°W) is built on an alluvial plain. Historically, it was a walled city surrounded from the northeast to the southwest by the Guadalquivir River (Fig. 2). This river separates the traditional neighbourhood of Triana from the remainder of the historic urban centre of Seville. Therefore, the extramural neighbourhood of Triana was connected to the intramural area of the city of Seville by a floating bridge (or pontoon bridge) that crossed the Guadalquivir River (Fig. 2). This floating bridge, originally built in 1171 A.D., consisted of a set of tall boats anchored to the bottom, joined together by iron chains, with wooden columns that held the platform of the bridge. By observing old lithographs, it is possible to deduce that the distance between the water surface and the platform of the bridge was no more than two and a half metres. It was reported that the bridge was damaged several times and even ripped and broken apart by the current in 1794 (Borja Palomo, 1878).

Figure 2 around here

The walls of the city of Seville have historically served two defensive purposes: military and hydrological purposes. The initial construction of the wall dates from the period of Julius Caesar (1st century B.C.). Since the Roman Age, it has been rebuilt and expanded. In the late Middle Ages, the wall was seven kilometres long and had 166 turrets, with 19 gates and wickets. Since the 16th century, its military purpose has been less important, and it was maintained to protect the city against the flooding river. It is the fundamental protective element of the city. During flood events, its gates were externally reinforced with caulked planks inserted in lateral guides. It is important to highlight that in1868, after great political debate, the gates and walls were torn down with the justification that this would favour the expansion of the city. However, this would also influence the impact of floods on the city, as described in subsequent sections.

Similarly, the drain spindles of the city of Seville were closed during floods to prevent them from working in the reverse direction (i.e., introducing water from outside of the city into the walled urban centre). In the river plain of the opposite riverbank, next to the neighbourhood of Triana, cloisters and monasteries were built, which appear frequently in historical records as being affected by river flooding. After floods, a serious additional problem was the permanent ponding of the low areas of the river plain, where poor quality water bodies formed, with pests and the risk of disease transmission, as was reported for different periods by Borja Palomo (1878).

Two tributaries flowed through the west side of the city, which are currently channelled and hidden: the Tamarguillo, currently a ring road for traffic, and the Tagarete, closer to the walls (Fig. 2), which crossed under the bridge that provided access to the Xerez Gate in the southwest of the city. This location is a very relevant aspect since the height of the old city wall is a reference that was used by some chroniclers to note the danger of the floods. Both tributaries increased the destructive flood effects on the city. Moreover, Guadalquivir River is influenced by the rhythm of the tides at its mouth; high tides oppose the flow of the river current, which hinders river discharge during floods.

In the 7th century, the old canal of La Vega was opened to serve as a natural drain that prevented the risk of overflow into the city and that was maintained and improved during Muslim rule. However, with the Christian Reconquista (13th century), the maintenance of the canal was neglected, and its depth decreased, which increased the flood risk. During the 17th-19th centuries, important containment and diversion works were proposed, although most of them were never implemented.

In 1776 the sewerage system was enhanced and a pier was built that improved the defense of the city against floods. In 1816, different reformations were carried out along the course of the Guadalquivir River between its mouth and the city of Seville to facilitate navigation throughout the river and reduce the risk of flooding.

It is worth mentioning the severe floods of 1892 and 1895, when the city was not protected by the wall. In the 20th century, several overflows also occurred, generally with small impacts, of which there is extensive journalistic and graphic documentation. During the 19thcentury and especially the 20th century, hydraulic works were carried out in the river and in the flood plain, such as the cutting of meanders and canals or reservoirs (García Martínez and Baena, 2006), which have substantially modified the natural dynamics of the river and the risk of flooding.

2.2 Historical documentary sources

The present study is fundamentally based on the documentary proxy data obtained from the historical monograph Critical history of the floods of the Guadalquivir in Seville from its reconquest to today (“Historia crítica de las riadas o grandes avenidas del Guadalquivir en Sevilla, desde su reconquista a nuestros días” in Spanish) by Francisco de Borja Palomo (Fig. 3). Borja Palomo (1878) gathered data on the historical floods of Seville and their effects on the city between the 13th and 19th centuries, and for all years with floods, he compiled all the known documentary sources.

Figure 3 around here

This book is complex and was written by scholar and bibliophile Borja Palomo (professor of jurisprudence at the University of Seville and official receiver of the city hall of Seville) in the late 19th century. In addition to the detailed critical compilation of annual floods, he also included notes, biographical comments of distinguished figures, descriptions of relevant and catastrophic events (earthquakes, hurricanes, epidemics, famines, etc.) and a description of some monuments. He provided paintings with a view of the city and its relationship with the river, as well as images of the old gates of the city wall. The book is divided into two volumes. The first volume covers the period between the Christian Reconquista (13th century) and 1800 A.D. and compiles and expands upon the articles that were previously published by the author. The second volume is focused on the 19th century and was published later (1884).This later volume incorporates other manuscripts. In each of the years when there were reports about floods, the book includes comments on the primary documents written by chroniclers who were contemporary to the event or had direct references. Similarly, the second volume includes texts of historians who highlighted the effects of the floods with a broader perspective. We have consulted primary sources in files and historical records of different institutions that corroborate the reliability of the corresponding comments by Borja Palomo (1878). As an interesting example, we highlight the dissertations presented at the Regia Sociedad de Medicina y Ciencia of Seville after the floods of the 18th century stand out, focused on the medical damages that floods can cause.

The data of Borja Palomo (1878) have been used in studies that analyse the change in the geomorphology of the Guadalquivir River during the Holocene (Uribelarrea and Benito, 2008), the sinking of the flood plain as a consequence of the growth of the city Seville (Ruiz-Constán et al., 2017) and the flood risk of the Guadalquivir River (García Martínez and Baena, 2006), as well as the fact that it has been cited as a source of studies on historical floods in Andalusia in the 16th century (Pfister et al., 1999) and throughout the 20th century (León González-Mazón et al., 2020).

One of the most laborious tasks involved in acquiring information related to historical climatology and hydrology is consulting multiple documents with varied content in archives and libraries of diverse ownership. Borja Palomo (1878) gathered over four hundred works, most of them related to the history of Seville and the floods of the Guadalquivir River: records, annals, memorials, ephemerides, relations, appendices, speeches, dissertations, etc., of numerous authors throughout history. Among this vast number of documents, he highlighted, based on the number of citations and the authority granted to its comments, the “Ecclesiastical and Secular Annals of

Seville" by D. Diego Ortiz de Zúñiga (1638-1680). This author gathered, in his memoirs, data on the period between 1246 and 1671 A.D. According to León González-Mazón et al. (2020), the book of Borja Palomo (1878) is a bibliographic source of inestimable value for its clarity and the details of its information. It is also cited in the National Catalogue of Historical Floods of Spain (Dirección General de Protección Civil y Emergencias, 2019).

2.3 Links of floods with meteorological instrumental records

Similarly, the Royal Observatory of the Navy of San Fernando (Cádiz, southwestern Spain) has uninterrupted pluviometric records from 1805, although with homogeneous monthly series from 1837. It is considered as a reference observatory due to the homogeneity of its temporal series, which is the longest series for southern Spain (Rodrigo, 2002; Sousa et al., 2010). A recent study, which analysed 25,423 pluviometric observatories in 32 geographical areas worldwide, highlighted that the observatory of San Fernando has the longest uninterrupted daily series (Morbidelli et al., 2020). San Fernando is not located in the Guadalquivir Valley (it is 30 km away from the mouth of the Guadalquivir River), although it is in the same drainage basin, i.e., the Andalusian South Atlantic basin. Different authors have applied the evolution of the monthly precipitation series of San Fernando as an indicator for the entire southwestern region of the Iberian Peninsula (Sousa et al., 2009; 2015; García-Barrón et al., 2013; 2018). During the 19th century, reports about floods partially overlapped with the instrumental rainfall records of the observatory of San Fernando.

After the summer period in which the monthly precipitation of July and August is frequently null, the precipitation of the beginning of autumn is incorporated into the subsoil, therefore, except for occasional torrential rains, the runoff of streams and the flow in the tributaries of the Guadalquivir does not present a notable increase until the end of autumn.

3. Methodology

3.1. Methodology used to estimate the severity of the floods between the late 13th century and the 18th century

To calculate the severity of the floods reported between the 13th and 18th centuries so that the severity values can be compared, we must standardise the information obtained from documentary sources of different origin (by author, date and content). Thus, we established source-contrast systems that allowed the subsequent classification of very different flood events, selecting the following main criteria: a) the height reached by the overflow on the wall or on one of the gates of the city, b) the damage caused by the collapse of buildings and c) the number of people drowned.

Other secondary criteria to standardise the range of severity of the floods were a) the evacuation of exterior buildings (private homes and cloisters), b) livestock mortality in the flood plain of the Guadalquivir River in the vicinity of Seville, c) effects on the floating bridge or on the ships of the harbour and d) rogations and other religious ceremonies.

Apart from these criteria and with the aim of establishing the severity of the flood events, we used a triple filter that modulated the classification assigned to them by the different documentary sources to compare their severity levels:

. The relevance of the social and urban impacts in the urban area of Seville with which they appear in the compilation of events conducted by Borja Palomo (1878).

. The appreciation of the authors themselves and the comparison with similar events gathered in records and annals of long periods.

. Whether they were gathered in the main records or only in particular references.

Appendix I shows, in a comparative manner, the main and secondary criteria employed to assign the overflow level and impact of the different flood indices, as well as the filters that were applied to modulate the classification of the severity of the floods.

Guided by these criteria, we assigned an ascending index of flood severity as a function of the level of the overflow and its impact:

- Index Flood I.- Flooding with the gates and spindles of Seville being closed and flooding of the extramural neighbourhoods, with the evacuation of the flood plain of the Guadalquivir River in the vicinity of Seville.
- Index Flood II.- Alarm in the city with the rampart or gates endangered, collapsed buildings and flooding in the lower intramural areas.
- Index Flood III.- Serious generalised catastrophic situations in the entire city, except in higher areas.

Each of the testimonies about specific events highlights some of the above-mentioned aspects, without the possibility of establishing a common typology. Thus, it was necessary to conduct a comparative evaluation of the information provided in each case. We recognise that the application of the previous criteria to each year with a registered flood is subject to personal valuation margins of the authors of the original documentary sources. To control this subjectivity, the descriptions of the different documentary sources were transformed into numerical tables based on the flood indices (see Appendix II). Others documentary sources consulted can be seen in Appendix III.

3.2. Methodology used to calculate the severity of the floods reported in the 19th century and their relationship with instrumental meteorological records

The second volume of Borja Palomo (1878) is focused on the floods that took place in Seville during the 19th century. The information provided by different documents compiled by this author is not uniform throughout the 19th century. The description about the effects of the overflow cannot be directly compared to those in previous centuries, mainly due to the large construction works carried out in 1776 with the building of a pier in front of the walls, and later in 1816 with the construction of a canal that reduced the risk of flooding. Thus, these elements modified the severity of the impacts that served as classification criteria in this study for previous centuries.

The average of the instrumental series from the 19th century shows that in the Guadalquivir River Valley, the intra-annual distribution of precipitation increases in autumn until it reaches a monthly maximum in November-December and decreases progressively in spring (García-Barrón et al., 2013). The interannual variability of the seasonal changes of the precipitation regime is associated with the North Atlantic Oscillation (NAO) in the Iberian Peninsula (Trigo et al., 2004), which, in its negative phase, favours the entry of storms in the Guadalquivir River Valley (Gallego et al., 2006; García-Barrón et al., 2018). This current behaviour can be extrapolated to previous centuries (Luterbacher et al., 2002).

During the first half of the 19th century, the classification of the severity of floods of the Guadalquivir River was based on the description of the effects caused by the floods. However, from 1858 to the end of the 19th century, we generated a quantified series of river overflows that allowed us to establish the possible degree of synchronous correspondence between the temporal series of both climatic manifestations: precipitation versus overflow. For each flood, we identified the height the river reached over the usual level. In the Guadalquivir river basin, floods are generally due to persistent rainfall and not to very short and intense rainfall events. This period of persistent rains precedes the more intense rainfall that ends up leading to the overflow of the channel. According to the revised historical documentation, in the surroundings of Seville, the floods used to last several weeks. For this reason, we use the data for the month in which the maximum overflow occurred and also the data for the previous month (bimonthly). For that reason the meteorological variable used for correlation test was the excess of bimonthly precipitation at San Fernando respect to the average of the period 1837-1890.

To synthesise the temporal development, we generated a new series, based on the flood index, that shows the rainy sequences or periods between the late 13th century and the 19th century using the centred moving average was calculated for 11-year periods. In general, from the 16th century the number of documentary sources available for the same event has progressively increased. This means that the information available is also greater, which does not necessarily imply that the number of floods is therefore more frequent or intense.

4. Results and interpretation

4.1 Severity of the floods between the late 13th century and the 19th century

A classification of the Guadalquivir River floods, based on the flood severity index assigned, between 1290 A.D. and the late 18th century is shown in Figure 4. Although there is temporal continuity, to visualise the flood events in more detail, these events were grouped by century. More specifically, Figure 4a represents the 13th, 14th and 15th centuries; Figure 4b shows the 16th century; Figure 4c displays the 17th century; and Figure 4d shows the 18th century.

Figure 4 around here

13th-15th centuries

Despite the limited number of authors and the difficulty in preserving documents disseminated by copyists before the arrival of printing, news of floods before 1500 A.D. have been transmitted. Some of these reports are focused on the spread of diseases rather than on direct property damage. We interpreted that because this information had been recorded as extraordinary events by chroniclers, they were relevant.

In the 250 years of the late Medieval Period (1250 to 1500 A.D.), twelve floods of remarkable impact were described (Fig. 4a). Three of them were classified as extremely disastrous (Index Flood III), specifically in 1297, 1403 and 1485. Before 1290, there is no record of floods in the book of Borja Palomo. During the first half of the 14th century, the incidence of floods was very low, and then, in the second half, there were floods of different categories.

From the flood of 1403 to 1481 only that of 1435 was reported, which suggests that the pluviometric regime for that period the Guadalquivir River Valley was characterised by scarce overflow. Considering the number and effects of the floods, we can estimate that globally, over the studied time period, the 15th century, except for the two last decades, was a period with the lowest flood incidence.

16th century

Ten floods were recorded throughout the 16th century, although six of them took place in the last decade of that century. The flood reported in 1595 was classified as a generalised catastrophe in the city (Index Flood III). This suggests that the last decade of the 16th century was very rainy and that the remainder of the century had very few flood events.

17th century

Although only ten floods were reported in the 17th century (in 1626, 1649 and 1683), these floods can be considered among the most catastrophic floods during the analysed centuries (Index Flood III). Except for 1650-1682, in which no overflow of the Guadalquivir River was recorded, the remainder of the century presents a relatively uniform distribution, with a trend of approximately 7-10 years. Precisely, this period of 1650-1682 coincides with the first half of the Maunder Minimum (1645-1715; Eddy, 1976; Usokin, 2017), which, under our criteria, supports the idea that the decrease insular activity corresponded to a dry period in southern Spain, although the continuity of the Maunder Minimum, from 1683 to 1715, was relatively more humid (Alcoforado et al., 2000).

Through the analysis of the ecclesiastical tithe between 1589 and 1708, Rodrigo (2007) established that in the area of Seville, thirty years of bad harvests were recorded, of which sixteen years could be attributed to excess precipitation, among other possible causes such as frost and locust plagues and the Plague epidemics. In the same period, nineteen floods of different categories were recorded. Over nine years, the excess rainfall coincided with floods. However, among the bad harvests, such analysis did not include the serious floods of 1595 or, especially, 1626; the latter was called “the year of the deluge” (“el año de diluvio” in Spanish). No floods were recorded in any of the seven years classified as bad harvest years.

The solemn public supplications are an important means of understanding the historical evolution of the climate. In the investigations based on ecclesial documents they take on a remarkable weight. Although Borja Palomo (1878) collects multiple news on supplications related to the Guadalquivir River, his analysis is even broader, since he also includes other documentary sources that he directly describes the level that the water reaches in each flood and its urban and social impacts.

18th century

Twelve overflows of the Guadalquivir River occurred in the 18th century, and those in1707 and 1758 had catastrophic effects (Index Flood III). During the second half of the 18th century, the occurrence of moderate and serious events increased (Index Floods II and III). García Martínez and Baena (2006) also found an increase in the frequencies of Guadalquivir River floods from 1750 with respect to the previous centuries. The greatest rainfall variability was detected in 1730 and 1780. The first years of the 1780s were very dry; during the winter and spring of 1780-1781 and the spring of 1782, there were marked episodes of drought, as confirmed by the pro pluvia rogations. On the other hand, strong rains prevailed from 1784 (when the floating bridge of the Guadalquivir River was moved) onwards.

In summary, Table I shows the number of reported floods between 1280 and 1800 as a function of the flood impact index assigned, the probability of occurrence per decade and the average period of recurrence in years.

Table I around here

Table I shows that, on average, the city of Seville has had approximately one flood every 12 years, of which one every fifty-eight years had catastrophic effects. Therefore, it is possible to confirm that the flood risk in the urban area of Seville was a historically usual element. Thus, flooding was a consistent focus and concern for the authorities and the population.

4.2 Severity of the floods during the 19th century

Section I of Volume II (1800-1858) of Borja Palomo (1878) describes ten overflows of the Guadalquivir River. The recorded documentary sources differ in the type of information they provide in different years, although they are consistent in the use of platforms ("borriquetes" in Spanish) raised above the floating bridge of the Guadalquivir River to connect to the neighbourhood of Triana (1803, 1830 and 1841). In January 1823, the main catastrophic flood of this period took place, which inundated the entire neighbourhood of Triana and reached the height of the previous great flood of 1796. We can assert that in the first half of the 19th century, the frequency of floods of different intensities was high.

Section II of Borja Palomo (1878) describes historical episodes of the city that were not directly related to the river flooding. As a novelty, Section III provides uninterrupted data from 1858 on the height (feet) reached by the river during each flooding event. Table II shows the years and months of maximum overflow and the corresponding elevation over the usual level of the river.

Table II around here

Moreover, as noted in the methodology section, we used the monthly rainfall series of the San Fernando Observatory (southwestern Spain) to calculate the bimonthly excess precipitation with respect to the average of that in 1837-1890, coinciding with the floods. The flood of 1876-77 was not used in the calculations since after the demolition of most of the gates and the walls of the city in the preceding years, the river flooded the city. Therefore, without protection, there was no longer a uniform criterion to compare the effects of previous floods.

Figure 5 shows a pair diagram between the synchronous series of bimonthly excess rainfall p (l/m2) and the overflow level d (inches). Although the number of data points is small, it can be observed that the dots are roughly aligned.

Figure 5 around here

The small number of events and the type of variables that led to Equation 1 do not allow extrapolation to previous centuries, although the R squared explaining more than 70 % of the variance (Pearson's correlation coefficient R = 0.84 p = 0.073 and the standard error of the estimates is 3.78).

$$p = 9.4\, d - 28.5 \qquad (1)$$

The average of the instrumental series from the 19th century shows that in the Guadalquivir River Valley, the intra-annual distribution of precipitation increases in autumn until it reaches a monthly maximum in November-December and decreases progressively in spring (García-Barrón et al., 2013). The precipitation regime is associated with the North Atlantic Oscillation (NAO) in the Iberian Peninsula (Trigo et al., 2004), which, in its negative phase, favours the entry of storms in the Guadalquivir River Valley (Gallego et al., 2006; García-Barrón et al., 2018). This current behaviour can be extrapolated to previous centuries (Luterbacher et al., 2002). Figure 6 shows the intra-annual rainfall distribution (Fig. 6a) and the intra-annual distribution in the number of floods (Fig. 6b) showing the delay in the month with the highest probability of floods (January), with respect to the maximum of the intra-annual rainfall distribution (November-December).This could be due to the fact that floods are frequently influenced by not only immediate direct rain but also accumulated rain in a drainage basin.

Figure 6 around here

Between the start date of the uninterrupted instrumental series of rainfall records (1837) and the year of the last reports about floods gathered by Borja Palomo (1878) it is observed the following:

- In each of the 16 years with floods (see Appendix II), the total annual precipitation was above the average precipitation of the entire period.
- The average annual precipitation of the years with floods was 847 mm, which is significantly different from the average of 580 mm for the entire period of 1837-1878, that is, 46% over the annual arithmetic mean of the same period.
- For this period the average rainfall in the two wettest months of the year was 125 mm in November and 119 mm in December. However, in the years with floods the average of the month when the flood occurred was 143 mm and the average of the previous month was 184 mm. Therefore, the excess of the bi-monthly accumulation corresponding to flood events is 35% higher than that of the wet bimesters.

4.3 Interdecadal-scale estimation of the pluviometric evolution in the Guadalquivir River basin based on the records of floods in Seville

Frequently the floods of the Guadalquivir River are due to the accumulation of intense rains for several days in the context of a wide period of some weeks with rainy conditions. In general, this type of temporary distribution of rainfall is usually associated with the existence of west-south-west Atlantic fronts.

Using the results obtained in sections 4.1 and 4.2, it was possible to generate an inter-annual series of the flood index from the 13th to the 19th century. From the results of the annual flood indices for 1297-1796 (Fig. 4 and Appendix II), the centred moving average was calculated for 11-year periods (Fig. 7). The values of the Y coordinate represent the temporal variation of the flood index. This allows to establishing a comparable ordinal scale, for more than 5 centuries, which estimates the historical evolution of floods in the southwestern Iberian Peninsula.

Figure 7 around here

Figure 7 shows a non-periodic alternation of years with flooding and non-flooding intervals. During the 14th century, a moderate level of floods can be observed; however between 1580 and 1650 there is a long sequence of flooding. Finally, from 1680, three discontinuous pulses are shown with a greater amount of flooding episodes: 1680 to 1710, 1730 to 1760 and 1770 until the end of the 18th century.

Rodrigo et al. (1999) presented conclusions on the temporal development of precipitation in southern Spain based on several types of historical reports in different localities between 1500 and 2000, with instrumental records for the 19th and 20th centuries. We observed a generalised likelihood between their pluviometric evolution and the one obtained in the present study for the same periods in both studies (1500-1800 A.D.). The authors highlighted the positive anomaly or the humid period from the late 16th century to the mid-17th century.

Barriendos (2007), through a documentary analysis of institutional sources and ecclesiastic pro pluvia rogations, used two complementary ordinal indices of precipitation and drought. This author highlighted that in Seville, two periods of floods, one from 1580 to 1620 and the other from 1760 to 1800, occurred. He also identified two drought periods: 1560-1580 and 1660-1730. Generally, his results are globally consistent with those presented in this study, with no discrepancies at the multi-decadal scale. The results obtained by García Martínez and Baena (2006) from a geomorphological analysis of the study of floods in the lower Guadalquivir River are also in line with our results.

It seems probable that the effects of the Little Ice Age (LIA) on the Mediterranean latitudes were markedly more humid and with greater variability with respect to those on the northern latitudes of Europe (Sousa and García-Murillo, 2003). Pfister et al. (1999) stated that climate change on the Iberian Peninsula could be more associated with precipitation and less associated with temperature. Grove (2001) highlighted that the same climatic conditions that induced the advance of glaciers during the LIA were also responsible for an increase in the frequency of floods and sedimentation in Mediterranean Europe. Several studies (Barriendos and Martín-Vide, 1998; Rodrigo et al., 1999, 2000) detected, with different aspects, humid periods during the LIA in Andalusia (1570–1630, 1780–1800 and 1830-1870), which alternated with dry periods and with great variability (Benito, 2006; Rodrigo, 2018). Similarly, different studies have detected greater aridity in the climatic conditions of the Doñana Biosphere Reserve, which coincided with the end of the last of the humid periods of the LIA on the southern Iberian Peninsula, and these conditions influenced the deterioration of lagoons (Sousa et al., 2010), hygrophytic plants (Sousa et al., 2013) and coastal streams (Sousa et al., 2015).

In comparison with other studies, based on different types of qualitative sources of information and through different assignation procedures, the results of this study must be interpreted in their own context. The concept of drought can result in multiple interpretations in general, which refer to a deficit of precipitation. Therefore, although different authors that documented historic climatology used terms that, in a simplified manner, identify with dry/rainy, these do not have an unambiguous meaning, but they introduce conceptual differences depending on the applied methodology and the type of precipitation variable estimated.

5. Conclusions

This study briefly presents the impact of Guadalquivir River floods on the urban area of Seville, especially highlighting the city walls as a protective element against such events. These particular conditions influenced the levels of impacts cited in texts. From the literary description of the historical floods of the Guadalquivir River, we generated an index flood series from the late 13th century to the 19th century. In addition, we created transference criteria that numerically assigned three ascending levels of severity as a function of the described impacts. We developed graphs for each century that show the intensity of the floods (and, complementarily, multi-annual sequences with no floods). Of the ten floods classified as most destructive in the five centuries analysed (1280-1880), five were concentrated during little more than a century, i.e., between 1598 and 1701.

We consider that a multiple-century application of floods is an adequate procedure that, in addition to other proxy data, contributes to the knowledge of the historical climatic evolution on the southern Iberian Peninsula.

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Appendix

Appendix I. Impact and overflow levels applied to the three flood indices with which the historical floods of the Guadalquivir River between 1250 and 1800 A.D. were characterised, as well as the criteria and filters used to categorise the impacts.

Index Flood	Overflow level and impact	Main criteria	Secondary criteria	Filters to modulate the classification of the impact
I	Closing the gates of the city of Seville and the spindles. Flooding of extramural neighbourhoods, with the evacuation of the flood plain in the vicinity of Seville.	a) Height reached by the overflow on the wall. b) Damage caused by the collapse of buildings. c) Number of people drowned.	d) Evacuation of extramural buildings. e) Livestock mortality. f) Effects on the floating bridge or on the ships in the harbour. g) Rogations and other religious ceremonies.	The relevance with which a flood appears in the compilation of events. The recognition of a flood byte authors and comparisons with similar events. Whether the floods are included in the main records or only in particular references.
II	Alarm in the city with the rampart or gates endangered. Collapsed buildings. Inundation in the lower intramural areas.			
III	Serious generalised catastrophic situation in the entire city, except in higher areas.			

Appendix II. Years of significant Guadalquivir River flooding (1297-1876) with indication of the month of the maximum overflow of the river and estimated severity index. For the 13th and 14th centuries the historical source only indicates the year and during the 19th century the severity index is not applicable.

Century	Year	Month	Index
13th	1297	-	3
14th	1330	-	2
	1351	-	1
	1353	-	2
	1363	-	1
	1373	-	1
	1383	-	2
15th	1403	November	3
	1435	February	2
	1481	December	1
	1485	February	3
	1488	December	1
16th	1507	November	1
	1522	January	1
	1544	January	2
	1554	January	2
	1590	March	2
	1591	March	1
	1592	December	1
	1595	November	3
	1596	Mai	1
	1597	January	1
17th	1603	December	1

	1608	March	1
	1618	March	2
	1626	January	3
	1633	September	1
	1642	January	1
	1649	April	3
	1683	January	3
	1691	March	1
	1697	Mai	1
18th	1707	March	3
	1709	February	1
	1736	April	1
	1739	December	1
	1740	January	0
	1745	February	1
	1750	October	1
	1758	January	3
	1777	February	2
	1784	January	2
	1786	March	1
	1792	January	1
	1796	November	2
19th	1802	December	-
	1804	January	-
	1806	April	-
	1821	January	-
	1823	January	-
	1830	January	-
	1831	January	-
	1838	February	-

	1839	December	-
	1841	January	-
	1843	March	-
	1845	January	-
	1846	January	-
	1852	December	-
	1855	March	-
	1856	January	-
	1858	November	-
	1860	December	-
	1862	January	-
	1866	March	-
	1867	January	-
	1872	January	-
	1876	December	-

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Tables

Table I. Distribution of floods based on the annual index flood, with probability of occurrence and average recurrence period.

Index Flood	Number	Average probability of occurrence per decade	Average recurrence period (years)
I	23	0.44	22.6
II	12	0.23	43.3
III	9	0.17	57.8
Total	44	0.85	11.8

Table II. Month and year of the most relevant floods and the corresponding elevations of the level of the river (in inches).

Date	Nov-1858	Dec-1860	Jan-1862	Jan-1867	Jan-1872	Dec-1876
Elevation of the level of the river	21	12	16	28	22	37

*The impacts of this year cannot be compared with the other floods of the 19th century.

Figure captions

Figure 1. Location of Seville and the Guadalquivir River on the Iberian Peninsula.

Figure 2. View of Seville with the Guadalquivir River in the 17th century. This map shows the floating bridge or bridge of boats at the lower left side and the Torre del Oro at the right end of the harbour. Source: detail of the enlarged facsimile version of the Atlas *Civitates Orbis Terrarum* (1588) by Braun and Hogenberg. It can be found online at the National Geographic Institute of Spain. Available at https://www.ign.es/web/catalogo-cartoteca/resources/html/023677.html (Accessed 2020 April 16).

Figure 3. Original cover of volume I "*Critical history of the floods of the Guadalquivir in Seville*" published in Seville in 1878.

Figure 4. Index flood estimated for the Guadalquivir River in Seville: a) 1290 A.D. to 15th century, b) 16th century, c) 17th century and d) 18th century.

Figure 5. Scatter plot of the elevation of the river level, measured in inches, and bimonthly excess rainfall, measured in mm, with the regression line indicated.

Figure 6. Intra-annual distribution: a) relative rate of monthly rainfall during the instrumental period and b) intra-annual distribution in the number of floods.

Figure 7. Decadal-scale estimation of the flood index evolution in the Guadalquivir River basin based on the flood records for Seville between 1250 and 1800 A.D.

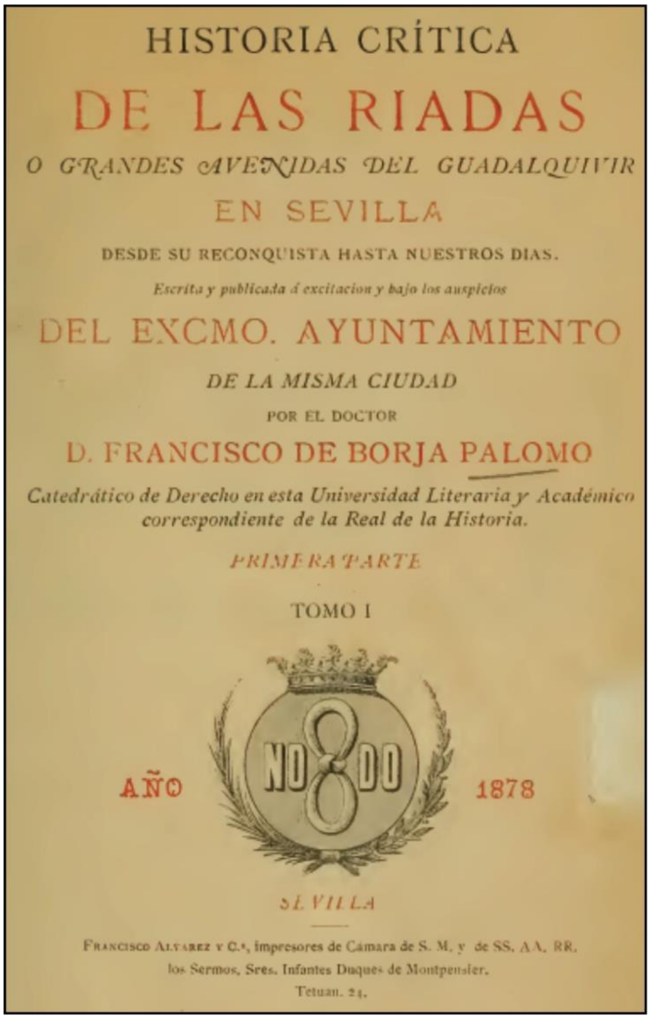
Figure 1


10°0'0"W
5°0'0"W
0°0'0"
5°0'0"E
40°0'0"N
FRANCE
N
River Miño
River Douro
River Ebro
PORTUGAL
MADRID
River Tagus
River Júcar
LISBON
River Guadiana
River Segura
River Guadalquivir
SEVILLE
CORDOBA
CADIZ
San Fernando
Gibraltar
ATLANTIC OCEAN
MEDITERRANEAN SEA
0
100
200 km
Europe
Spain
Africa

Figure 2


City walls
Guadaquivir River
Tagarete stream
Sevilla
Guadalquivir River
Bridge of boats
RIO DE GVADALQVEVIR
Triana
Guadaquivir River

Figure 3



HISTORIA CRÍTICA

DE LAS RIADAS

O GRANDES AVENIDAS DEL GUADALQUIVIR

EN SEVILLA

DESDE SU RECONQUISTA HASTA NUESTROS DIAS.

Escrita y publicada á excitacion y bajo los auspicios

DEL EXCMO. AYUNTAMIENTO

DE LA MISMA CIUDAD

POR EL DOCTOR

D. FRANCISCO DE BORJA PALOMO

Catedrático de Derecho en esta Universidad Literaria y Académico
correspondiente de la Real de la Historia.

PRIMERA PARTE

TOMO I

AÑO 1878

SEVILLA

Francisco Alvarez y C.ª, impresores de Cámara de S. M. y de SS. AA. RR.
los Sermos. Sres. Infantes Duques de Montpensier.
Tetuan. 24.

Figure 4

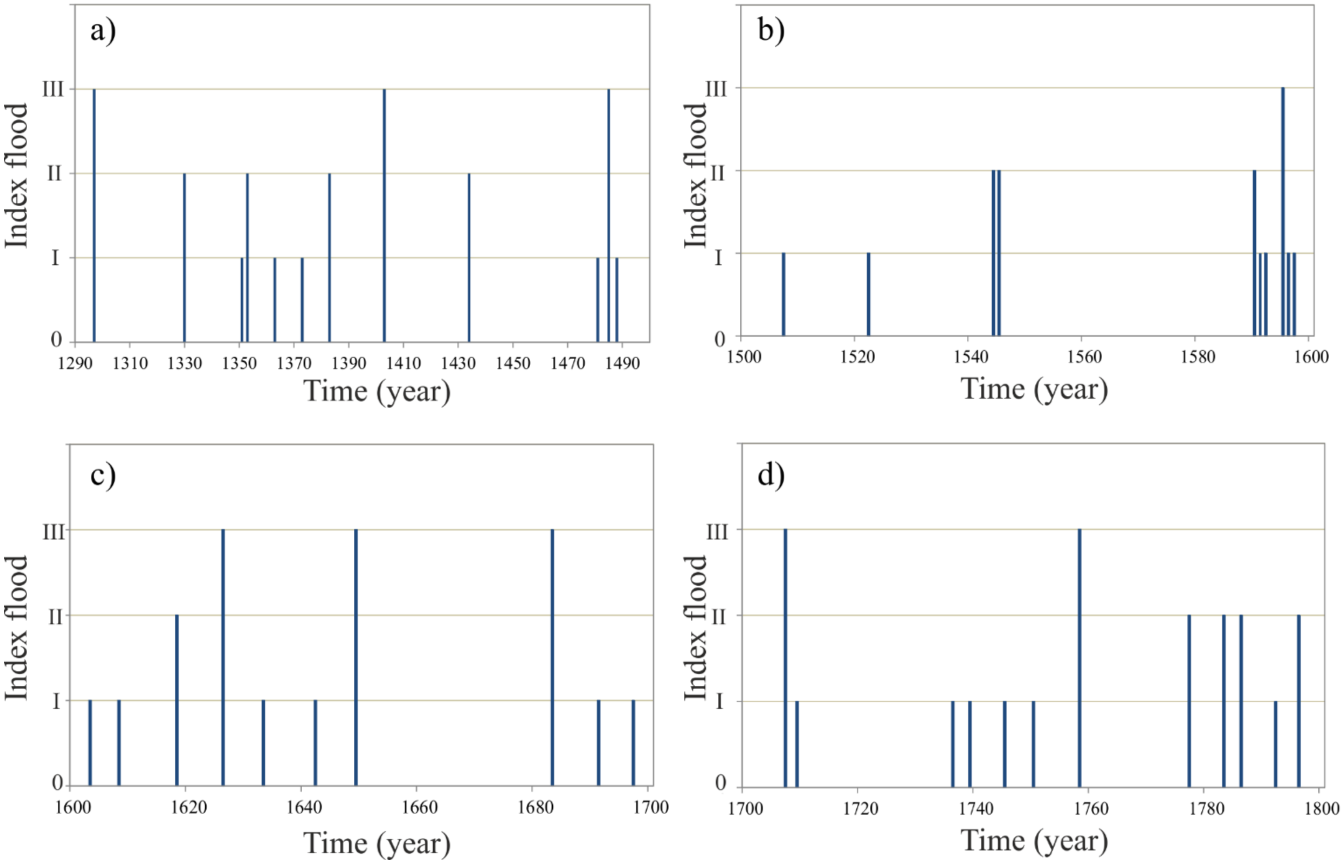
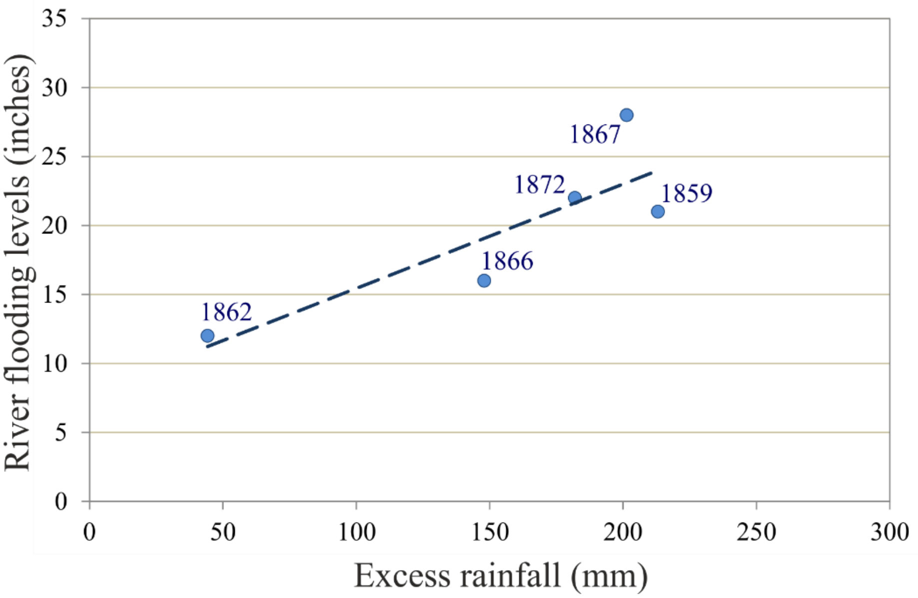

a)
b)
c)
d)
Index flood
0
I
II
III
Time (year)
1290
1310
1330
1350
1370
1390
1410
1430
1450
1470
1490
1500
1520
1540
1560
1580
1600
1620
1640
1660
1680
1700
1720
1740
1760
1780
1800

Figure 5



River flooding levels (inches)
35
30
25
20
15
10
5
0
0
50
100
150
200
250
300
Excess rainfall (mm)
1862
1866
1872
1867
1859

Figure 6

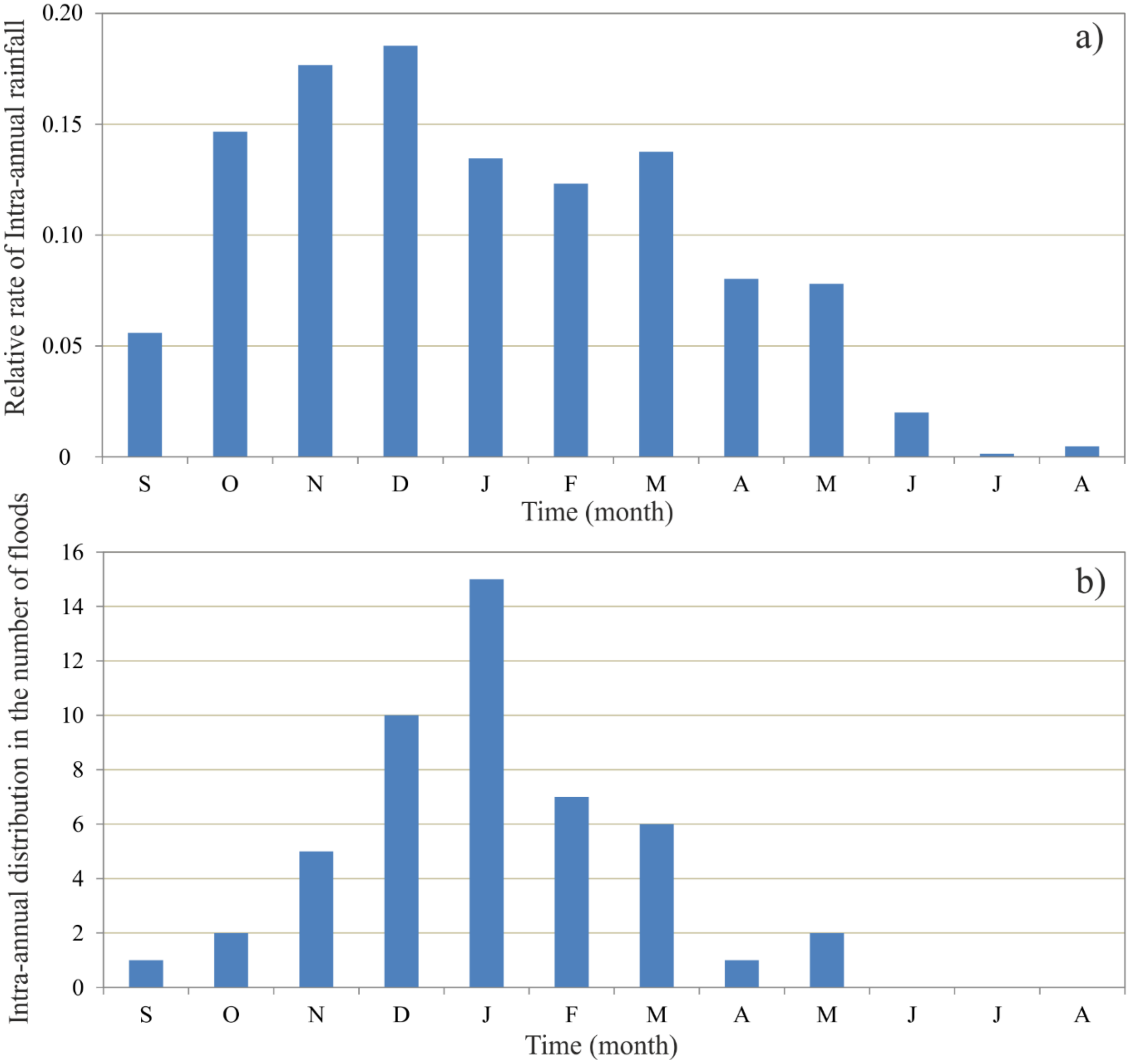
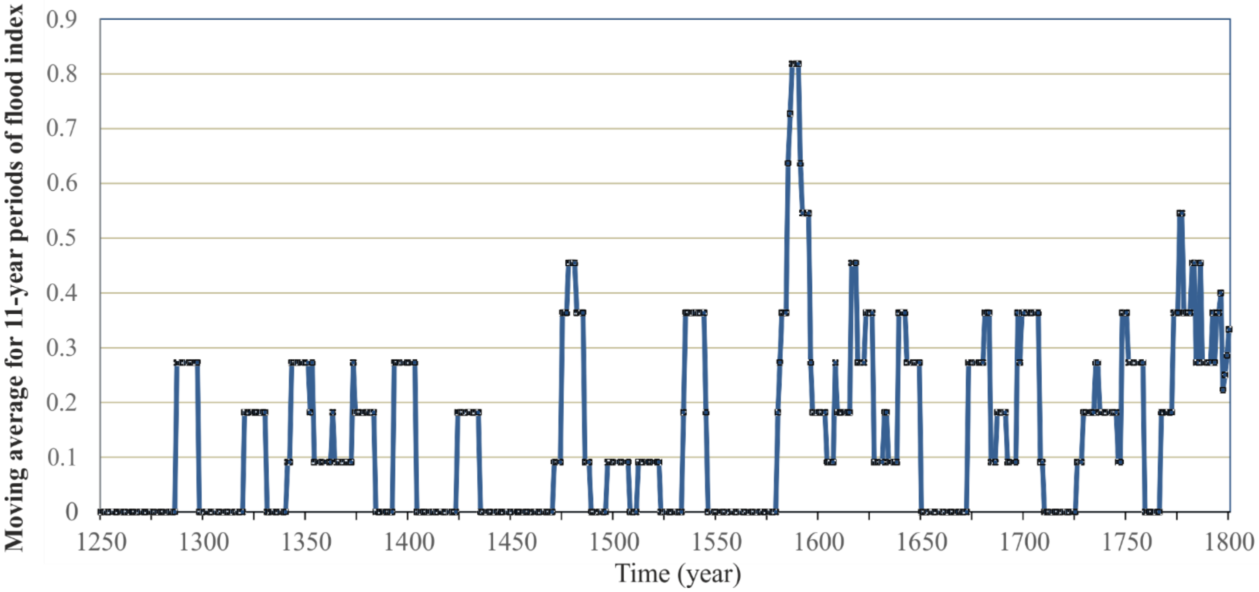

a)
Relative rate of Intra-annual rainfall
0
0.05
0.10
0.15
0.20
S
O
N
D
J
F
M
A
M
J
J
A
Time (month)
b)
Intra-annual distribution in the number of floods
0
2
4
6
8
10
12
14
16
S
O
N
D
J
F
M
A
M
J
J
A
Time (month)

Figure 7


Moving average for 11-year periods of flood index
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1250
1300
1350
1400
1450
1500
1550
1600
1650
1700
1750
1800
Time (year)