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Relationships between precipitation and floods in the fluvial basins of Central Spain based on documentary sources from the end of the 16th century

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Abstract. This study presents the results of a historic reconstruction based upon documentary sources of precipitation and floods during the last fifty years of the 16th century in Central Spain. We used data from primary sources contemporary to the events rather than compilations or secondary references. These documents belong to the institutions that administered the study area during the time period of interest and consist of municipal or monastic minute books and administrative texts from properties belonging to the nobility and royal family. Direct data that explicitly describe meteorological or flood-related events are haphazardly distributed throughout personal correspondence and various reports, and the sizes of floods or precipitation events can also be deduced from indirect data. We analysed the qualitative data by transforming them into numerical indices of intensity/duration for precipitation and intensity/area for floods. We differentiated three sets of years that presented different hydrological patterns. The first period, from 1554 to 1575, exhibited regular precipitation patterns associated with low-intensity floods. The second, from 1576 to 1584, was characterised by low precipitation levels and few floods. The third, from 1585 to 1599, showed intense precipitation with large floods interspersed with long-lasting droughts. We interpret these results in the context of the environmental and land-use patterns of the time period studied, which coincided with a period of low temperatures.

1 Introduction

The central Iberian Peninsula exhibits a continental Mediterranean climate and lies on both sides of the mountains of the Iberian Central System. Runoff channelled from these mountains reaches the fluvial basins of the Duero River to the north and the Tagus River to the south. Glacial cirques formed on the mountaintops during the Pleistocene, and abundant snow accumulation still occurs in winter, along with periglacial activity associated with numerous freeze-thaw cycles (Fig. 1).

The divide formed by the Iberian Central System, which runs from northeast to southwest, acts as a biogeographic boundary. Precipitation decreases progressively with distance from these mountains. Temperatures are also moderated from this central point outward but remain lower toward the north than toward the south. In general, supra-Mediterranean bioclimatic conditions are maintained in the northern basin, whereas a typical Mediterranean climate dominates in the southern basin (Tagus), with a tendency toward aridity (Peinado-Lorca and Rivas-Martínez, 1987).

Notable climatic reconstruction studies for the central Iberian Peninsula include those on precipitation and droughts conducted by Dominguez-Castro, et al. (2008) and Rodrigo and Barriendos (2007). These researchers studied areas located to the south of our study area, and they utilised annual cereal production data and information conserved in the cathedral of Toledo concerning rogation ceremonies. Among publications related to the 16th century in Europe, those of Glaser et al. (1999) report fluctuations in temperature and precipitation, while those of Brázdil et al. (1999) concern flooding events. Global overviews of the methodology and interpretation of historical climatology during past centuries in Europe can be found in individual works (Pfister, 1984; Pfister and Brazdil, 1999; Glaser, 2001, 2008) and in collective works (Garcia-Herrera et al., 2005; Brázdil et al., 2006; Glaser et al., 2010; Luterbacher et al., 2010; Zorita et al., 2010).

The morphological and biogeographical histories of the main rivers of the Tagus basin are well known (Alonso et al., 1988; Molina, 2002; Uribelarrea et al., 2003). Historical flood events in the Duero basin have also been compiled in a previous study (Loureiro, 2003). Contemporary data for

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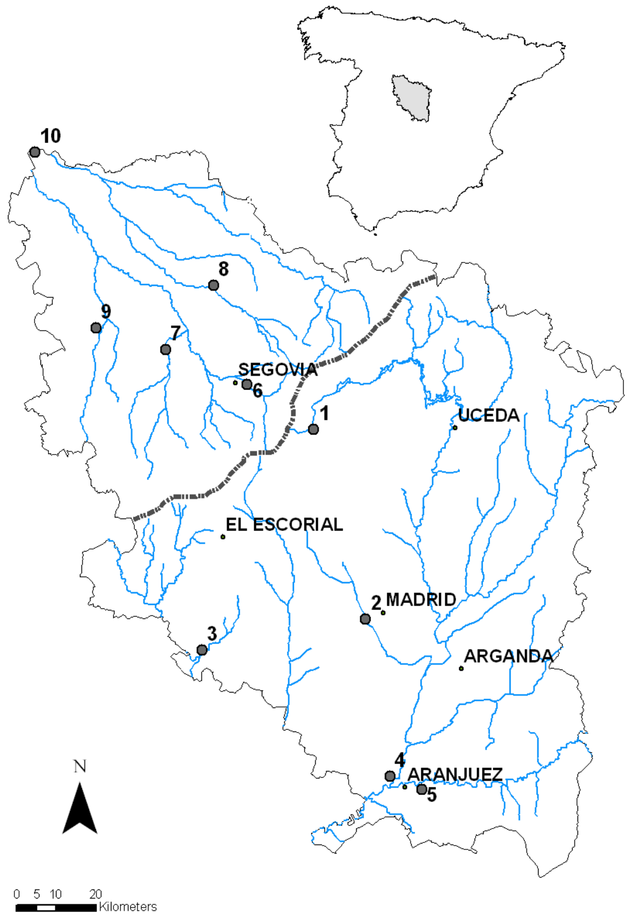

Fig. 1. Map of the study area, corresponding to the geographic region covered by the analysed documents. The Duero river basin is located to the north, and the Tagus river basin is located to the south. The extent of the map is based upon the administrative borders of Madrid and Segovia. Broken line = Spanish Central System divide; numbers = gauging stations.

the Tagus basin show strong inter-annual oscillation of the peak discharges of all rivers in the basin, although it is difficult to accurately establish the natural irregularity due to the intensive regulation of the rivers through the construction of upstream reservoirs (Gallego, 2006). Furthermore, it is difficult to determine the discharge volumes of larger floods due to limitations of the gauging stations. Therefore, reconstructions based on documentary data provide a valuable complement.

Based on sedimentary studies of palaeofloods in the Tagus basin downstream from the study area, previous studies (Benito et al., 2003a, b, 2008; Thorndycraft and Benito, 2006) have established that, although the maximum discharge recorded during the Holocene is 4100 $m^3 s^{-1}$, most of the large floods with a stratigraphic record during this period had volumes close to 2000 $m^3 s^{-1}$. These authors indicate that the peak discharge of the largest floods in the study area during the historic period from 1563 to 1599 was greater than 400 $m^3 s^{-1}$. According to reconstructions of landmarks, the largest known contemporary flood (in 1878) had a peak discharge of more than 1000 $m^3 s^{-1}$.

This study concerns climatic variability in inland areas of southern Europe and the analysis of climatic conditions in the 16th century, a period for which very little climatic or hydrological information exists. A large amount of previously unpublished flood data is also presented herein. Consequently, the present study greatly increases our knowledge of natural river regimes long before the existence of gauging records. Our research contributes to the collection of historic records for use in flood prevention, as outlined in European Directive 903/60, which relates to the evaluation and management of flooding risk.

The specific objectives of the present study are (1) to identify the different kinds of floods described in the documents analysed; (2) to define the relationships between floods and precipitation; (3) to analyse the differences and similarities in the data between the two river basins in the study area; and (4) to define the principal features of hydrometeorological trends at the end of the 16th century.

2 Methodology

We used written documentary sources that provide direct information relating to the impact of hydrological and meteorological events on people, goods, and services. By transforming qualitative data into numerical indices, we also obtained information about the intensity, magnitude, and frequency of such events from these documents. We consulted documentary collections held in the Palace General Archive; the Simancas General Archive; the National Historic Archives; the Archive of the San Lorenzo del Escorial Monastery; and the Segovia, Madrid and Torrelaguna Municipal Archives and manuscript sections located at the Spanish National Library and the British Library.

2.1 Data acquisition

Data were collected directly from sources contemporary to the events. The veracity of the compiled data is supported by its high level of temporal and spatial coherence and by the correspondence between the events described and those referred to by other people on the same dates and in other places. These various primary sources were not only unacquainted with each other but also had different interests.

The sources consulted were documents conserved by the administrators of the territory involved, which in the 16th century had a complex property structure. The area was governed, sometimes in an overlapping manner, by municipalities owning vast areas of land; nobles possessing large territories in an almost feudal regime; monasteries with the capacity to control land uses and the corresponding production;

and the royal family, which sometimes acted in the manner of nobles with territorial interests and sometimes as a legislator and enforcer of laws that affected everyone.

We consulted the following types of documents:

1. Municipal minute or agreement books, characterised by highly formal, concise written records. These records often provide data about the damages caused by rainfall or flooding to buildings, bridges, vegetable gardens, and forests. They also provide detailed descriptions of day-to-day life such as problems relating to market supply; the effects of droughts, cold snaps, or excessive rainfall; disease outbreaks; and other needs of the population.

2. Monastery minute books. These documents are highly formal and provide the most objective and continuous data, including records of the wheat trade and books reporting the tithes levied on annual cereal production. Furthermore, these documents occasionally contain reports on particular events of interest.

3. Administrative documents from property belonging to nobles. These documents include contracts to exploit pastures and woods; requests to plant crops on new land; land-use regulations in villages belonging to the nobility; and collections of files describing incidents such as repairs to roads, bridges, and riverbanks.

4. Royal administrative documents. These documents contain reports on the state of natural areas and of buildings, dams, bridges, and structures meant to protect royal properties against river floods. We also examined collections of private correspondence from the royal family to their secretaries, administrators, nobles, and abbots directly describing various events, including weather. In addition, we consulted collections of bills and invoices from the dates of interest referring to repairs to royal buildings. These records sometimes indicated the cause of the damage, which was frequently related to rainfall or rivers overflowing their banks.

It was not possible to extend our analysis to later centuries because around the 17th century, many of the sources employed ceased to provide the required information or disappeared completely.

After collecting the relevant information, we organised the data into coherent clusters based upon one or several well-characterised events. To these clusters, we added information with similar dates that lacked significance in isolation but that could enhance or complete the final interpretation. We interpreted and verified the information by checking its concordance with well-documented historical facts and the absence of contradictions between different sources of information from the same date. We performed fieldwork based on the inferred scenarios to determine the geomorphological, hydrological, and climatic contexts of the events. Likewise, we consulted cartographic drawings from the area to establish the locations of places, properties, and demarcations that do not currently exist (Kagan, 1989; Bullón, 2006).

2.2 Data interpretation

To interpret the data, we first assigned an occurrence date to each event. Although the documents were usually dated with a day, month, and year, the events described therein could refer to different time scales. We then categorised the type of information obtained. The resulting compilation contained both explicit data concerning large increases in river flows or precipitation, which usually included the location, intensity, and date, and implicit data concerning flooding damage or rainstorms and their consequences. We therefore designated two data categories:

1. Direct data, which explicitly describe a meteorological or flood-related event, sometimes with information about the resulting damages or observable consequences. These data are haphazardly distributed throughout a variety of documents. They do not constitute systematically collected datasets intended to objectively record these events. The main sources of direct data are personal letters, reports on the state of nature, and explanations and reasoning relating to the events that had taken place. To interpret these data, we considered the professional station of the author, his responsibility for the statements contained in the document, and the public or private nature thereof.

2. Indirect data, which refer to associated damages or benefits without directly mentioning the phenomenon responsible. There are three categories of indirect data: (1) those relating to biological development, including the number and state of health of game animals, croplands, pastures, and forests; (2) geomorphological and fluvial dynamics causing erosion or sediment load in rivers; and (3) damage to structures situated on riverbanks or floodplains such as mills, dams, bridges or buildings, or to roofs or walls which may deteriorate during precipitation events. Because the quality of these structures differed greatly from that of present-day structures, it is difficult to estimate the scope of precipitation or flooding based upon the damage caused to buildings or public works. To interpret these data, we estimated the relative resistance of each type of structure by noting the frequency with which it was seen to deteriorate.

2.3 Conversion of data into numerical indices

We calculated numerical indices to enable statistical analysis of the data. Transforming qualitative data into numerical values is a standard practice in studies of historical climatology or hydrology (Glaser et al., 1999; Glaser, 2001; Barriendos and Coeur, 2004; Brázdil et al., 2005; Brázdil et al., 2010; Llasat et al., 2004; Martin-Vide and Barriendos, 1995). We followed criteria based upon the procedures used by these previous authors, but we designed our own indices adapted to the peculiarities of the data employed.

The data on both precipitation and floods primarily express the extent of the phenomena. This information is also implicitly contained in records concerning the durations of precipitation events and the magnitudes of floods. Consequently, we used the following concepts to define our quantitative indices:

Intensity: The estimated extent of an event, which is the best-documented datum passed down to the present time.

Duration: The temporal development of an event, which is related to the cause of the atmospheric instability that gave rise to the precipitation event. This index was used to represent the three most frequent types of precipitation in Central Spain, which are well documented for the central Iberian Peninsula. These types are convective precipitation events, which are locally and temporally limited; precipitation events caused by wet spells, which produce rain or snowfall that tends to last several days or weeks; and situations of generally persistent instability lasting more than one month or season, which occur when the value of the North Atlantic oscillation index is negative (Lopez-Rey and Yagüe, 2009; Pauling et al., 2006).

Area: This index is based upon the hydrological stream ordering of the channel segment involved in a documented flood and differentiates between floods of similar intensity in different sectors of a basin because the discharge volume of a flood differs between the riverhead and lower river sections (Tables 1 and 2).

All of these criteria were integrated to obtain combined indices of intensity/duration for precipitation and intensity/area for floods. The intensity of both floods and precipitation events was considered to be the clearest and most dominant parameter, whereas duration or area was complementary and introduced some variation among events of similar intensity. The final value of each of these combined indices was calculated as the sum of 70 % of the intensity value and 30 % of the duration (precipitation) or area (floods).

The qualitative concepts described in the texts were converted into numerical values according to the following criteria.

2.3.1 Precipitation

Intensity: 1 = occurrence of precipitation without any qualification or associated damages; good crop and pasture growth of crops and pastures; good health of wild animals (deer) during the autumn; and favourable tree growth. 2 = Intense precipitation, usually associated with damage to roofs and collapse of walls exposed to rainfall; destruction of roads, streets becoming rivers, widespread appearance of water seepage and pooling in buildings; and cereal harvests that fail to mature in the spring due to excessive moisture. 3 = Extraordinary precipitation with obvious damage or consequences, generally represented by direct data and associated with large floods.

Duration: 1 = one or several days; 2 = several weeks; 3 = one month or more.

2.3.2 Floods

Intensity: 1 = annual or seasonal floods causing little damage; generally beneficial in sections with floodplains in terms of fertilising the land or irrigating crops, pastures, and trees; any other increase in discharge volume causing little damage to trees or riverbanks and debilitated bridges or barges. 2 = Floods damaging well-built infrastructure; erosion or obvious accumulation of gravel on riverbanks; transport of timber along a badly damaged river. 3 = Extraordinary floods causing generalised damage, with water invading wide floodplain areas; major destruction of economic goods; drowning of many domestic and wild animals; inaccessibility of bridges over regional rivers, destruction or serious damage to bridges over large rivers; and modifications in channel shape. These floods frequently occurred simultaneously in the Tagus and Duero basins.

Area: 1 = Headwater sections and ephemeral streams; 2 = hydrologically well-organised mid-river sections with permanent discharge; 3 = regional sections draining a wide, shallow area.

Some examples illustrating the qualitative conversion of precipitation and flood data from original texts are given below.

Example 1: "This Saturday at midday eight days ago, it started to rain and has not stopped since." (Simancas General Archive, April 1570); intensity = 1, duration = 2.

Example 2: "The rains have been very heavy here and have soaked the foundations of the stables and the mangers are full of water; the same thing occurred one year ago." (Simancas General Archive, June 1567); the conversion assigned thereto was intensity = 2, duration = 3.

Examples of the qualitative conversion of data on floods are: *Example 3*: "In the month of May, I passed over the Fuenfría mountain pass and found that the streams had destroyed the royal road from the Guadarrama summit, leaving many stones scattered on it." (Palace General Archive, May 1564); the assignation given thereto was intensity =3, area =1 because the event occurred in a riverhead section, where movement of the sedimentary load in streams is unusual.

Example 4: "...the rivers are very swollen and it is not possible to cross them." (Simancas General Archive, January 1574); intensity = 2, area = 2 because this flood affected local rivers.

Example 5: "There have been big floods; the river has invaded the floodplain, causing serious damage and drowning the small game." in the lower river section of the Tagus river basin, and "The year was so rainy and there were so many

Table 1. Mean annual discharge and peak discharge of river sections in the Tagus basin, showing the range of area used to calculate the quantitative indices. The locations of the gauging stations are shown in Fig. 1.

River/number in Fig. 1	Mean Annual discharge ($m^3 s^{-1}$)	Peak Discharge ($m^3 s^{-1}$)	Basin size (km^2)	Height (m)	Area score
Lozoya/1	1.41	46.2	42	1270	1
Manzanares/2	2.165	120.52	505	537	2
Perales/3	0.667	79.66	261	497	2
Jarama/4	36.998	1854.4	11 549	491	3
Tajo/5	33.35	211	9340	490	3

Table 2. Mean annual discharge and peak discharge of river sections in the Duero basin, showing the range of area used to calculate the quantitative indices. The locations of the gauging stations are shown in Fig. 1.

River/number in Fig. 1	Mean Annual discharge ($m^3 s^{-1}$)	Peak Discharge ($m^3 s^{-1}$)	Basin size (km^2)	Height (m)	Area score
Eresma/6	3.41	58.92	252	900	2
Moros/7	2.12	93.76	252	940	2
Pirón/8	1.26	51.05	172	869	2
Voltoya/9	0.82	70.16	140	1089	2
Duero/10	35.40	774.08	12 740	690	3

Source for Tables 1 and 2: Hydrographical Studies Centre (CECEX): http://hercules.cedex.es/anuarioaforos/afo/estaf-mapa_gr_cuenca.asp and also author.

floods that the miller was ruined…" in the middle river section of the Duero river basin (Archive of San Lorenzo del Escorial Monastery, July 1591); intensity = 3, area = 3 for the Tagus basin, and intensity = 3, area = 2 for the Duero basin.

2.4 Statistical data analysis

The resulting data series were standardised. We then employed three different groups of statistical analyses:

1. First, we constructed cross-tables containing annotations for each year and season of floods and precipitation, with three possible states: coincidence of floods and precipitation in the same season and year; only precipitation in a particular season and year; or only floods in a particular season and year. The coincidence of precipitation and floods in the same season and year reflects the quality of the information compiled. When only precipitation is indicated, the information may be complete; but if only floods are recorded in a given season and year, the data may be incomplete and/or the effects of the floods may have been greater than the precipitation events that caused them. The absence of data was interpreted as a year or season with little precipitation. Second, we determined the different intensities of the floods and precipitation events.

2. We studied the statistical characteristics of the series of intensity scores for both precipitation events and floods using the most appropriate normality test based upon the basic statistics defining these series.

3. We examined the temporal evolution of the precipitation and flooding patterns by examining the smoothed standard curves using a five-year moving average to test the medium- and long-term variability of the data and Mann-Kendall's nonparametric sequential test. Finally, we calculated the slope of the linear regression versus time in cases of statistical significance.

3 Results

3.1 Results of the cross-tabulation

In the Duero basin, floods and precipitation events coincided in 20 % of cases during the spring and 18 % during the winter. The data recorded precipitation only in 13 % of cases during the spring and 11 % during the winter. The data recorded floods without any indication of precipitation in 4 % of cases during the spring and 11 % during the winter. In the Tagus basin, floods and precipitation events coincided during 16 % of cases during the spring and 12 % during the winter. Precipitation without floods occurred in 14 % of cases during the spring and 11 % during the winter. Floods without precipitation data occurred in 2 % and 4 % of cases during the spring and winter, respectively. The similarity of the data for the two basins indicates the quality of the information obtained. However, the number of floods not associated with wintertime precipitation in the Duero basin appears high, which may indicate a deficit of precipitation data during this season of the year.

In the combined dataset, 17 % of cases during the spring and 20 % of cases during the winter represented coinciding precipitation events and floods; 9 % and 10 % of cases during the spring and winter, respectively, represented precipitation only; and 3 % and 5 % of cases during the spring and winter, respectively, represented floods only. This fusion of the data for the two basins improves the data structure, especially in reference to winter, because the co-occurrence of precipitation and floods increases while the occurrence of precipitation or floods alone decreases (Table 3).

Floods coincided in both basins during 13 of the 34 yr in which such events occurred, although the flooding was not always of equal intensity in the two basins. Events during the spring coincided more often (40 %) than those during the winter (30 %). The largest and most widespread floods occurred in 1557, 1591, and 1594.

3.2 Precipitation and flooding data series in the Tagus and Duero basins

3.2.1 Determination of intensities and frequencies

Floods occurred (with or without damage) during a total of 31 yr in rivers within the Tagus basin and during 19 yr in the Duero basin. The total number of flood records across all seasons was 51 in the Tagus basin and 29 in the Duero basin. The correlation coefficient (r) between precipitation events and floods was 0.68 in the Tagus basin and 0.55 in the Duero basin. In the Tagus basin, 41 % of floods were isolated or caused no damage, 36 % of floods caused some damage, and 23 % of floods caused generalised damage. In the Duero basin, 30 %, 55 %, and 15 % of floods were grouped into each of these categories, respectively. In the Tagus basin, the riverhead was affected in 9 % of cases, mid-river sections in 33 % of cases, and lower river sections in 52 % of cases. In the Duero basin, these percentages were 13 %, 78 %, and 9 %, respectively. Floods occurred from October to January and from March to May, decreasing considerably from June to September. Floods were concentrated during the spring (35 %), autumn (23 %), and winter (33 %) in the Tagus basin and during the spring (43 %), autumn (15 %), and winter (42 %) in the Duero basin. In the Tagus basin, 66 % of springtime floods occurred in lower river sections, but winter and autumn floods occurred along all river sections, including the riverhead. No appreciable seasonal differentiation occurred in the Duero basin. Some isolated floods during the summer

Fig. 2. Standard five-year moving average curves of floods (solid line) and precipitation (broken line) in the Tagus basin. Y-axis = deviation from normal value; X-axis = yr.

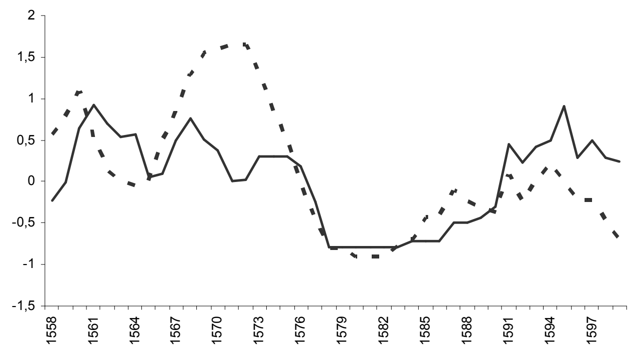

Fig. 3. Standard five-year moving average curves of floods (solid line) and precipitation (broken line) in the Duero basin. Y-axis = deviation from normal value; X-axis = yr.

and autumn indicate a certain degree of exceptional convective activity.

Abundant precipitation occurred during the autumn, winter, and spring of 1554 to 1573. However, precipitation declined substantially in subsequent years during all seasons, particularly spring, especially from 1574 to 1584. Precipitation levels partially recovered around the end of the century (Figs. 2 and 3).

The data from the Tagus and Duero basins reveal similar patterns of behaviour for both floods and precipitation events (Fig. 4). Regardless of other influences, the fundamental cause of this similarity is probably the existence of a similar rainfall regime in which the main agent appears to be the Atlantic precipitation fronts. These fronts reach the central Iberian Peninsula from October to December and from March to May. In both basins, their intensity increases due to the presence of the mountain range.

3.2.2 Statistical analyses

All of the series passed the Kolmogorov-Smirnov normality test. The Wilcoxon signed-rank test for related samples indicated no statistically significant differences among each

Table 3. Relationships between precipitation and floods in the Tagus and Duero basins.

		Tagus	Duero	Both basins
% Precipitations and floods	Spring	16	20	17
	Winter	12	18	20
% Precipitations	Spring	14	13	9
	Winter	11	11	10
% Floods	Spring	2	4	3
	Winter	4	11	5

Source: author

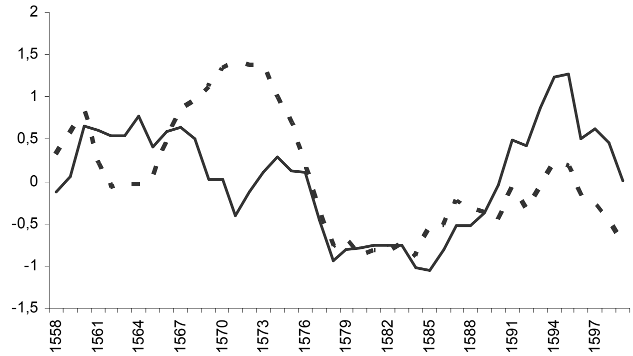

Fig. 4. Standard five-year moving average curves of floods (solid line) and precipitation (broken line). For both basins, Y-axis = deviation from normal values; X-axis = yr.

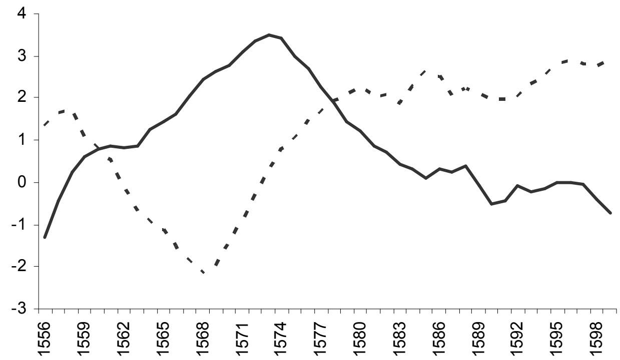

Fig. 5. Sequential Mann- Kendall curves of precipitations. Normal series (solid line), backward series (broken line). Tagus and Duero basins. Y-axis = Man-Kendall index (u_t) and ($u_{t'}$); X-axis = yr.

of the flood and precipitation intensity groups for the Tagus and Duero basins. The ρ Spearman and τ Kendall correlation coefficients were significant at the 0.05 level, with values of 0.399 and 0.231, respectively.

During the first period (1554–1573), the intensity of precipitation was greater than the intensity of minor floods. During the third period (1585–1599), precipitation was less intense, whereas floods were more intense. These trends occurred in similar proportions in both basins (Table 4). Springtime precipitation declined sharply from 1574 to 1599, compared with all previous years in each basin.

3.3 Combined analysis of precipitation and flood series

Groups of years that exhibited similar behaviour patterns in relation to floods and precipitation were indicated by Mann-Kendall's sequential test. In the test for precipitation (Fig. 5), we identified a well-defined phase ending around 1575 that corresponded to the period with the greatest abundance of precipitation. Another highly homogeneous phase began in 1576 and extended to the end of the data series. The overall trend of this series was negative.

Fig. 6. Sequential Mann- Kendall curves of floods. Normal series (solid line), backward series (broken line). Tagus and Duero basins. Y-axis = Man-Kendall index (u_t) and ($u_{t'}$); X-axis = yr.

In the sequential test for floods (Fig. 6), we found no appreciable general trend, although oscillations above and below the stability value occurred. An initial oscillation up to 1576 coincided with the period of maximum precipitation. Another phase, lasting until 1592, corresponded to low-intensity flooding. A third oscillation at the end of the data

Table 4. Percentages of floods and precipitation by basin and time period.

	TAGUS BASIN		DUERO BASIN	
	% Precipitations	% Floods	% Precipitations	% Floods
1554–1573	60	45	77	63
1585–1599	27	43	20	36

Source: author

Table 5. Correlations between precipitation and floods.

	ρ Spearman	α	τ de Kendall	α
Precipitation/yr	−0.54	0.00	−0.28	0.01
Precipitation/flood	0.53	0.00	0.34	0.00

Source: author

Table 6. Linear regression of precipitation slope.

	slope	error	significance
Precipitation/yr	−0.03	0.00	0.00

Source: author

series coincided with the large floods of 1594–1599. Despite these differences, the ρ Spearman and τ Kendall correlations between precipitation and floods were moderately high and significant (Table 5). The slope of the linear regression line was significant for precipitation, with a value of −0.03 (Table 6), but it showed no defined trend and was not significant for floods.

4 Discussion

The greater abundance of floods in the Tagus basin compared to the Duero basin is probably due to the greater hydrographic complexity of the former basin. The data from the Tagus basin refer to mid-river and lower sections, whereas those from the Duero basin represent the riverhead and mid-river sections. The high frequency of low-intensity floods in the Tagus basin is associated with the periodic inundation of the floodplains, which is a phenomenon that does not occur in the portion of the Duero basin considered here.

Precipitation exhibited a negative slope of −0.030 (Table 6), indicating that across the 45 yr considered, there was a global decrease of 1.38 points below the normal value of this series. This decline in precipitation was sharper during the spring than during the autumn and winter and had environmental and economic consequences. Many of the data collected indicate deterioration of the forests and the need to repair springs used to supply water to the population. Similarly, the lack of pastures during the springtime may have impaired livestock productivity. Studies of cereal harvests, which depend directly on spring rainfall, indicate that harvest volumes declined by 60 % during the 1590s compared with the previous wetter period (Bullón, 2009).

Comparison with current data shows substantial similarity to the historic records studied here. Wet and dry periods frequently alternate in the Iberian climate and characterised its evolution during the 20th century (Sousa et al., 2011). During dry periods, spring rainfall declines most (Paredes et al., 2006), especially during March in the western-central sector of the Iberian Peninsula. The precipitation data obtained here are also consistent with the precipitation reconstructions performed by Dominguez-Castro et al. (2008) and Rodrigo and Barriendos (2007).

Floods show no defined tendency, being equal in intensity at the beginning and end of the time period considered. The time lag between precipitation events and floods appears to be contradictory, although the results of the Spearman and Kendall correlations indicate that flood intensity corresponds with precipitation intensity: during 1567–1575, when precipitation was abundant, flood intensity was moderate; whereas during 1590–1599, when little precipitation was recorded, highly intense floods occurred (Figs. 2, 3, and 4).

The floods that occurred during the final years of the 16th century are well known. Benito et al. (2008) has listed the period from 1590 to 1610 among those exhibiting the largest floods within the Iberian Atlantic basins during the last 300 yr. This period was also characterised by severe droughts, and Rodrigo et al. (2001) have recognised the importance of the 1590s in the development of intense floods in Andalucía.

Numerous studies on the hydrology of Iberian basins, both Atlantic and Mediterranean, highlight the association between periods of drought and floods. The usual explanation for this pattern is based upon both the greater intensity of single precipitation events and the infiltration capacity of the hydro-environmental system following a prolonged period of drought. The texts consulted indicate that the inter-annual regularity of rainfall was lost during this period; therefore, some years had continuous precipitation whereas others had absolute drought. The intensity of precipitation events also appears to have been greater during this period.

Numerous studies conducted in Spanish experimental basins (García and Lopez-Bermudez, 2009) have shown that surface runoff increases with the intensity of precipitation events and with reduced capacity for soil infiltration resulting from previous rainfall, providing that land-use conditions remain stable. Our database does not provide explicit information on soil deterioration, but there are frequent reports concerning the abandonment of croplands due to a lack of resources. Due to debts, peasants would lose their farming tools and would have no money to buy seeds. The texts also contain many annotations related to the serious degradation of pastures and natural vegetation. Thus, without any major change in land uses, the region was subtly transformed due to the abandonment of agriculture and livestock farming activities. It is not possible to know how these changes may have influenced infiltration and run-off because the interactions between land uses and floods are controversial and poorly understood (Estrela et al., 2001; Hoffmann et al., 2010).

The hydro-meteorological events studied here coincided with cold snaps that brought abundant episodes of snow and ice (Bullón, 2008). Temperatures returned to normal during the 1590s after 30 yr of cold conditions. However, episodes of intense cold continued to occur, as described by J. LHermite in December of 1592 (LHermite, 1890): "*In Almazán, very cold in this winter season affects us greatly, and we therefore dare to say (in accordance with the opinion of others) that it cannot be colder in Holland or Germany than it is here, with continuous frosts and snows.*" Consequently, the decrease in precipitation was not associated with increased evapotranspiration, as generally occurs during droughts in the Iberian Peninsula. Also, the seasonal snow cover may have partially fused with the perennial snowpack on high mountaintops during the wettest and coldest years. The corresponding amount of water released into river channels upon the return to warmer conditions likely increased flood magnitudes. Similarly, the lesser flood intensity during the wet and cold period from 1565 to 1573 may have been due to the retention of precipitated snow in the mountains.

5 Conclusions

Quantitative conversion of qualitative information from documentary sources reflects the hydrological and climatic regimes of the study area. This study is representative of the typical hydro-meteorological characteristics of the central Iberian Peninsula during the time period analysed. Data from the basins located to the north and south of the Iberian Central System can be interpreted jointly because they respond to a similar precipitation regime in a regional context.

The differences observed between the two basins are mainly due to their different degrees of hydrographic complexity, which is greater in the Tagus basin than in the Duero basin. The greater aridity of the Tagus basin is offset by the presence of rivers with larger flows, resulting in more intense and more frequent floods.

We differentiated three time periods that presented different hydrological patterns. The first period, from 1554 to 1575, exhibited regular precipitation, causing floods of low intensity. The second period, from 1576 to 1584, was characterised by low levels of precipitation and flooding. The third period, from 1585 to 1599, featured intense precipitation with large floods alternating with severe droughts.

Although it is commonly accepted that the largest floods in Iberian basins (both Atlantic and Mediterranean) occur during times of drought, their high intensity during the final decade of the 16th century can be explained by an intense precipitation regime with annual and inter-annual irregularity. Increased surface runoff may also have played a role due to modification of the global hydric balance and due to the cold snap that occurred during the same time period.

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