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FLOODS IN SPAIN'S MEDITERRANEAN REGION: CAUSES AND EFFECTS

Inundaciones en la región mediterránea española: causas y efectos

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1. Floods in a global context

The importance of floods throughout the world is beyond doubt. According to the United Nations International Strategy for Disaster Reduction *(*UNISDR), Hydrometeorological risks are the most important natural risks in the world, and floods are the risk that affects the greatest number of people and property. Different databases corroborate this statement.

The international database Munich-Re (2018), indicates that during the last ten years floods have become the most recurrent natural risk, so much so that throughout 2017 345 events were registered worldwide, the consequences of which resulted in 6,505 deaths and damages worth approximately €30 billion.

The 2020 Annual Report of the Weather Climate & Catastrophe Insight reveals that floods are currently the second most economically lossy natural hazard in the world after tropical cyclones. In 2020, the number of extraordinary flood events has been 167, costing 76 billion dollars.

Detailed flood data is reported in more than 89 countries in the worldwide datasets of Sendai. For Spain, this database for the period 1416-2010 includes 19,751 floods, in which 24,318 deaths have occurred and 113,710 houses have been damaged.

The International Disaster Database (EM-DAT), which compiles worldwide data on natural hazards that have affected the world from 1900 to the present, shows how flood records rise to 5,386 and they constitute the largest of the natural risks, representing 35% of the total risks, followed by storms with 26.5%. Regarding Europe, floods are the second most important risk, behind mass movements with 648 events, and represent 24.4% of total risks. For Spain, there are only 38 records from 1950, but it should be mentioned that this database only collects the most important events.

Environmental change, together with the greater exposure of goods and people, is causing a disconnect between human groups and their environment. As evidenced by the trends in the data, there is an accentuation of the effects of the climate on societies, in the form of greater economic losses. If we consider the IPCC projections, the current scenario is very likely to worsen. Given that risk is increasing and will continue to do so, if such predictions are materialized by intensifying the severity of the hazard, it seems necessary to pay more attention to human factors issues to achieve adaptation strategies that reduce this trend as for losses.

In this sense, the first step is to consider floods as complex multidimensional and connected dynamic systems that integrate human and environmental variables. There is a consensus around the idea that the risk of a natural event, such as floods, is determined by the sum of three basic factors that make up this dynamic system: (i) natural hazards, (ii) the vulnerability of the communities, and (iii) the exposure of goods and people. Therefore, the condition of the above is only explained if that society is vulnerable. This is an assessment of special interest, since, in the case of floods, the occupation of floodplains can reveal a high global vulnerability.

On this basis, historical studies of flood episodes acquire singular importance, since they allow showing the evolution produced in terms of vulnerability, measured in terms of adaptation to climatic changes, as well as exposure to danger. The results of these works are very useful for the improvement of hydrological studies and derived planning and spatial planning. Some relevant examples of this type of work are included in this special issue.

With regard to risk management, research is currently incipient, but the need has arisen for tools and mechanisms capable of assessing the risk of societies to floods with greater precision, to establish measures of adaptability. For this, it is essential to carry out interdisciplinary studies. In recent years, this has been one of the great challenges and the work on the physical factor or danger and the human factor or vulnerability seem to have been quite separate. However, in special issues, such as the one presented here, it is intended to bring together the interests of the disciplines dedicated to one or another factor to achieve better results.

Evidence of the interest that floods arouse in the world are the review publications that have been made in recent years (Ologunorisa *et al.,* 2005; Cheng *et al.,* 2010; Salman and Li, 2018; Lindersson et *al.,* 2020; Díez-Herrero and Garrote, 2019, 2020). The bibliometric analysis on a world scale by Díez-Herrero and Garrote (2020), using the Web of Science database, to evaluate the historical evolution and future perspectives of the flood risk assessment, shows how the scientific production on the analysis of flooding has increased considerably in the last 25 years. In this study, despite the limitations derived from both the data sources and the analysis methodology used, the number of references found is remarkable and is expected to continue growing. With the keywords “Flood” and “Risk” these authors (as of June 22, 2020, for the period 1996-2020) found 22,934 references. Regarding the main research focuses detected, the following stand out: (i) the impact of global change and its components, (ii) coastal flooding and its economic consequences, (iii) studies of multiple risks and the interactions between the risk of flooding and other types of natural hazards and (iv) incorporation of the psychosocial aspects of flood risk. In the opinion of these authors, in the future, there will be a significant increase in publications due to factors such as population growth, increased urbanization, deterioration of infrastructure, and the potential impact of climate change.

For Spain, Díez-Herrero and Garrote-Revilla (2019) performed the same bibliometric analysis. In this case, with the keywords “Flood” and “Spain”, the number of references obtained was 3,857 for the period 1996-2019, showing, like the publications at a global level, a very notable increase in recent decades especially in the publications referring to flood risk. These authors consider that, in the future, interdisciplinary studies that combine aspects of the natural sciences and the social sciences, focused on non-structural mitigation measures, will prevail.

In the Mediterranean area, it is noteworthy that, both in the Sendai database and in the EM-DAT, the highest number of floods collected have occurred in this territory. On the Mediterranean coast, in general, and in Spain in particular, throughout history there have been numerous and important flood episodes, thus testifying to this: (i) the historical flood catalogs (CNIH); (ii) the analysis of historical documentation (Barriendos *et al.,* 2003; Llasat *et al.,* 2005; Blöschl *et al.,* 2020); (iii) the different databases such as FLOODHYMEX (Llasat *et al.,* 2013a and b), HIDREXMED, SHERE (Gilabert *et al.,* 2014), European Flood Database (Hall *et al.,* 2015), Munich-Re (2018), EUFF (Petrucci *et al.,* 2019), MEDIFLOOD (Barriendos *et al.,* 2019), SMC-Flood database (Gil-Guirado *et al.,* 2019); (iv) reconstruction of paleo-floods (Benito and Thorndycraft, 2005); (v) or the various studies carried out on different Mediterranean basins, such as those of the Ter rivers (Ribas Palom, 2008) Llobregat (Llasat *et al.,* 2001) Ebro (Ollero Ojeda, 2000, 2007; Espejo Gil *et.al.,* 2008; Ollero Ojeda and Sánchez Fabre, 2016), Turia (Almela, 1957; Sánchez Fabre and Ollero Ojeda, 2017) Jucar (Butzer *et al.,* 1983; Mateu, 1988; Carmona González and Ruiz Pérez, 2000), Segura (Romero Díaz and Maurandi Guirado, 2000; Romero Díaz, 2007; Castejón Porcel and Romero Díaz, 2014), Andalusian basins that flow into the Mediterranean sea (Capel Molina, 1987; Sánchez Ramos, 2010; Rodríguez Martínez and Mesa Garrido, 2016), and the Balearic islands (Grimalt and Rosello, 2011; Torrens Calleja *et al.,* 2016).

But floods are not history, according to Petrucci *et al.* (2019), in their study on "Flood Fatalities in Europe, 1980-2018", these continue to be a major threat to people, despite considerable advances in forecasting, management, defense and rescue, and the number of victims is expected to continue to rise in the coming years.

Along the same lines, other investigations carried out show very worrying data. Predictions indicate that, as floods and damage to people and property increase, they will increase considerably. According to the international study, coordinated by Blöschl (2020), in which 34 research groups from all over Europe have participated, and in which floods in Europe between 1500 and 2016 have been studied, it has been found that floods now cause damage worth more than € 100 billion annually, and the general trend of heavy flooding is increasing. The last three decades are among the most important periods in terms of frequency and magnitude of floods in Europe.

Another recent study, conducted by the World Resources Institute (WRI), estimates that the number of people affected by floods will double worldwide by 2030, reaching 147 million people, compared to the 72 million that were affected 10 years ago. In terms of economic costs, damage to cities will rise from $ 174 billion to $ 712 billion each year. But in 2050 it will be even worse because according to this report a total of 221 million people will be at risk and the losses will be 1.7 trillion dollars a year.

In Spain, the study published in Nature Communications (Kulp *et al.,* 2019) concludes that more than 200,000 people will be periodically exposed to coastal flooding caused by climate change and, in the worst-case scenario, the number rises to 340,000 in the year 2100. And in the Mediterranean region, due to its topographic and thermal characteristics, which contribute to presenting intense rainfall in short periods, the existence of numerous torrential basins that favor flash floods, or human settlements in flood areas (increasing exposure to risk), are factors that can favor the increase in catastrophic events.

The evidence mentioned on the growing problem of floods reveals a profound lack of adaptation, as the main aggravating factor, regardless of what may happen to the climate in the future. The study of flood risk in the Mediterranean area, which this issue covers, is especially revealing about this trend and what it may hold in the future to the rest of the world. The challenge is open and it is urgent and necessary to redouble efforts in the study and knowledge of the causative agents, especially vulnerability, in order, as far as possible, to establish preventive strategies and measures, supported by a level of certainty that only the results of research, such as these, provide us.

2. The contributions included in this number of CIG/GRL

Although we are aware of the number of publications that have been and are being made on floods, it is enough to cite just two of the most recent: the monographic issue of the Water magazine "Flood Risk Assessments: Applications and Uncertainties" (Diez-Herrero and Garrote -Revilla, 2020) or the book *Riesgos de inundación en España: análisis y soluciones para la generación de territorios resilientes* (López Ortiz and Melgarejo Moreno, 2020), derived from the congress on floods that was held in 2020, we considered that more of this type of event has to be analyzed, both from the point of view of their causes and their effects and future predictions. That is why *Cuadernos de Investigación Geográfica* has considered it appropriate to also dedicate a special issue to "Floods in Spain's

Mediterranean region" which, as has been shown in different studies, is one of the regions most affected by them and it is expected that in the near future it will also be.

The twelve articles that are collected here deal with different aspects of floods in a spatial scope that extends throughout the entire Spanish Mediterranean area from Catalonia to Andalusia, including the Balearic Islands. Ten of the articles have a regional dimension, while another two cover a larger space.

The monographic issue begins with a valuable contribution by M.C. Llasat, with the title "Floods evolution in the Mediterranean region in a context of climate and environmental change". This work analyzes the floods in various areas of the Mediterranean (Catalonia, southern France, and Italy, Greece, and Turkey) in a context of climate and environmental change, considering a holistic perspective that also includes adaptation measures. The author reaches important conclusions such as that: (i) there is insufficient evidence to affirm that river floods are increasing in the Mediterranean; (ii) flash floods in small non-gauged basins are increasing due to increased vulnerability and exposure; (iii) future projections point to an increase in heavy rains, especially in Mediterranean Europe, and an increase in the southern Mediterranean; (iv) by the end of the 21st century, a decrease in flood risks is likely to take place in some Mediterranean rivers in southern Spain and an increase in others (for example, the Ebro river); (v) the probability of high impact flooding will increase as the temperature increases; or that (vi) flood management should be approached from an integrated and holistic point of view that includes greater awareness of the risks among the population and their participation in the formulation of mitigation strategies.

In the second work, signed by A. Pérez Morales, A. Romero Díaz, and S. Gil Guirado, "Structural measures against floods on the Spanish Mediterranean coast. Evidence for the persistence of the "escalator effect", almost the entire scope is analyzed space of the Spanish Mediterranean, except for Andalusia. It has been carried out by cataloging the structural works (dams, channeling, and storm tanks) built in the basins of the Mediterranean from the beginning of the 20th century to the present. It has been observed how in the first half of the century the actions were mainly limited to the construction of rolling reservoirs and it was from 1950 on that growth in defense infrastructures for the new urban areas was observed. Through the mapping carried out, a differentiated spatial distribution is also verified between the types of infrastructures and basins. The authors conclude by stating that, in the Spanish Mediterranean, despite the construction of a huge number of infrastructures aimed at mitigating the risk of flooding, flood damage has not diminished, so it is necessary to reflect on the validity of these actions and it is necessary to consider other prevention measures.

Following a north-south structure of Spain in the appearance of works of a more regional nature, in this monograph, A. Ribas Palom and D. Saurí Pujol focused their attention on the Ter river basin with their study "What can we learn from the past? A century of changes in vulnerability to floods in the Ter river basin". Its objective has been to analyze, from a historical perspective, what have been the impacts of flooding in this basin in the period 1900-2020, focusing its attention on the three factors that, according to the approach to vulnerability proposed by the IPCC, intervene on the impact of floods: exposure, susceptibility, and adaptability. The results obtained indicate that, although exposure to floods has increased and damage has followed an upward trend, the vulnerability has decreased as a result of the decrease in susceptibility and, especially, a significant increase in adaptive capacity. Both in terms of victims and relative economic losses, the impacts of the floods would show a downward trend that, among other factors, tends to correlate positively with the increasing levels of economic development and well-being that this basin has experienced. Progress in flood forecasting and warning, together with emergency planning which helped to explain why large-scale events such as storm "Gloria" in January 2020 (an event associated for the first time with climate change) did not cause human casualties.

The authors A. Ollero, J.H. García, A. Ibisate, and M. Sánchez Fabre, with extensive research experience on this subject, propose an update of knowledge with the title "Updated knowledge on floods and risk management in the middle Ebro river: the Anthropocene context and river resilience". This is because the recent floods in the middle course of the Ebro have made it necessary to rethink and update the forecasting and management systems. In this research, the new maximum flow data modified in 2019 by the Ebro Hydrographic Confederation have been applied for the first time; trend changes have been observed (decreasing until 1996 and slightly increasing since 1996); variations in the frequency of events (longer and more complex, which can lead to greater damage); variations in seasonality (now concentrating floods in winter and spring); and the correction of the data and the expansion of the series has made it necessary to update the return periods, reducing the flow forecast for the reference periods. According to its authors, the present work marks a starting point or inflection, laying the foundations: i) towards new analyzes that must be developed when the revised hydrological series is prolonged in time, ii) towards the follow-up and adaptive evaluation of the new ones. risk management measures that are being implemented, so that they are sustainable and achieve the resilience of the river, and iii) a greater knowledge of floods and the risk, which should be transmitted to the population so that they increase their memory, their awareness, and with it, their resilience.

In the Valencian Community, with a different scale of work, A. Cerda *et al.* have carried out the work "Rainfall and water yield in Macizo del Caroig, Eastern Iberian Peninsula. Event runoff at plot scale during a rare flash flood at the Benacancil ravine". These authors undertake a study on a slope and pedon scale, which is where the runoff is generated and the origin of the water discharge, which will later produce floods. These investigations are especially important in Mediterranean areas with dry riverbeds ("Ramblas"), such as the Ramblas of the Coroig Massif that is analyzed here. From the experimental studies carried out, after eleven years of direct measurements in the field, it is concluded that, from a spatial point of view, there is a decrease in the runoff coefficient along the slope; and from a temporal point of view, runoff is concentrated in few rain events, which are precisely those that cause floods. Only one rain event (in eleven years of follow-up) of 140 mm day^{-1} connected the runoff from the plots with the Benacancil ravine.

Continuing in the Valencian community, A. Camarasa-Belmonte has developed his research entitled "Flash-flooding of ephemeral streams in the context of climate change". By analyzing the different databases, it is possible to observe how many of the floods occur in dry riverbeds suddenly. For this reason, it is not surprising that the author of this work considers that the Mediterranean boulevards imply a significant risk of flooding, historically underestimated due to their intermittent flow and the general ignorance about their hydrogeomorphological functioning. This article addresses key issues of rain-flow conversion and flood generation in boulevards, as well as their evolution in the current context of environmental change. Based on cincominutal data (SAIH-Júcar), the work has been carried out in two phases: (i) in the period 1989-2018, in four boulevards, the generation of floods at the basin scale has been determined, based on 138 events; and (ii) in the period 1989-2016, on a more general scale, the evolution of 698 rain episodes in the Júcar River Basin District has been analyzed, to infer what consequences environmental changes could have for the formation of floods in Ramblas. The results obtained suggest that the episodes tend to increase in intensity and decrease the accumulated precipitation. Climate change could lead to an increase in intense flash floods, which are increasingly difficult to manage with the usual flood control instruments, and secondly, there is a tendency towards progressive aridification of these Mediterranean basins. It is necessary to increase the hydrogeomorphological knowledge of ephemeral streams to develop solutions to current and future problems.

The causes that produce intense rainfall in the provinces of Alicante and Murcia have been studied by J. Martín-Vide, M.C. Moreno-García, and J.A. López-Bustins, under the title "Synoptic causes of torrential rainfall in South-Eastern Spain (1941–2017)". The work has determined the synoptic types of 68 dates in which torrential precipitation greater than 200 mm/day was recorded in the period considered, in any station in the provinces of Alicante and Murcia, representative of the southeast of the peninsula. For the same dates, the surface pressure, and the value of the Western Mediterranean Oscillation index (WeMOi) have also been considered. The results show the percentage importance in torrential rainfall in the Southeast of Spain of the eastern advection with DANA (isolated high-altitude depression) or 'cold drop' type, present in more than 50% of cases, followed by troughs in 500 hPa and dynamic or cold storms. Except for the latter type, the mean atmospheric pressure is close to or higher than normal. In all cases, the WeMOi was negative, which is consistent with the nature of this teleconnection pattern.

The episodes of intense rains that produce floods in the Segura basin, in general, and in the province of Murcia in particular, in recent years, have been frequent and with catastrophic effects. One of these episodes took place in September 2019 and A. Romero Díaz and A. Pérez Morales have carried out a study of this episode, using the press as a source for information. The objective of the work, entitled "Before, during, and after the DANA of September 2019 in the region of Murcia (Spain), as reported in the written press", was to analyze this episode through a follow-up of all the news published in two newspapers regional for 52 days. A total of 816 articles were analyzed and grouped into 26 topics. The database created made it possible to organize the information in different aspects and sequences: (i) prevention tasks and alerts before the materialization of a risk situation; (ii) rescue, relief, and assistance to people, and (iii) response, rehabilitation and reconstruction. From the analysis carried out, it cannot be concluded that the news that appeared in the press directly motivated response from the administration, but it is considered that they may have had a great influence. One year after the DANA episode, the panel of experts formed immediately after the event, has finally proposed a series of measures, intending to minimize the impact of the floods.

Another source of information, such as historical documentation, is that used by S. Gil-Guirado, J. Olcina-Cantos, A. Pérez-Morales and M. Barriendos in their study carried out in the city of Murcia, "The risk is in the detail: historical cartography and a hermeneutic analysis of historical floods in the city of Murcia". In this work, a hermeneutical analysis of the three most catastrophic floods that occurred in Murcia in the last 400 years is carried out and the analysis is completed with a quantitative historical cartographic reconstruction. Among the main conclusions reached by its authors, the fact that Murcian society had strategies for overcoming disasters that involved the whole of society and that advocated comprehensive management of emergencies stands out. However, the state of hardship before a flood is a determining factor to explain the resilience capacity of the social system. It is found that pre-industrial Murcian society used the mechanisms available to it to adapt to floods less efficiently. A hermeneutical analysis is important to transcend the mere description of the events that occur during a disaster and to highlight the problems and potentialities of each period in a historical key. The historical cartographic analysis has allowed a better understanding of the internal flooding processes, as well as a better characterization and contextualization of the complexity of the study area. Thanks to the use of old maps, it has been possible to delimit a historical region such as the Huerta de Murcia, which due to its complexity and internal structures escapes a simple administrative delimitation.

In the Andalusian Mediterranean region, J.M. Senciales-González and J.D. Ruíz Sinoga also try to know the climatic causes that produce recurrent floods. With their work "Features of weather types involving heavy rainfall along the southern Spanish Mediterranean", they propose a systematic comparison of synoptic conditions with events of heavy rainfall in southern Mediterranean Spain, evaluating the types of weather responsible for the meteorological risk in specific locations in this mountainous region. To do this, they analyze the maximum intensity of precipitation since 1943 in an observation period of 10 minutes to 24 hours, using an extensive database of 132 meteorological stations. Subsequently, heavy rain has been associated with the type of weather that triggers it. The study came to identify a pattern of intense rains different from that previously known in the Mediterranean area. Thus, the maximum number of intense rain events is usually caused by low pressures associated with front systems and winds from the East-Northeast, but the maximum volumes are usually associated with Cold Drops and the same winds. In the Alboran Sea, in southern Spain, a pattern of heavy rainfall was found that differs from that previously reported for the Mediterranean area. This was due to its geographical position, very close to the Atlantic Ocean, and the conjunction of latitude and orography.

In the same geographic area as the previous work, J. Ojeda Zujar, P. Fraile-Jurado, and J. Álvarez-Francoso, evaluates the risk of flooding, but in this case due to the rise in sea level. The objective of his work "Sea level rise inundation risk assessment in residential cadastral parcels along the Mediterranean Andalusian coast" is to present the main methodological results of the evaluation of permanent flood risks associated with the rise in mean sea level according to different scenarios and models. Climate change, focusing on the assessment of the danger, exposure, and physical vulnerability of built areas, especially residential areas on the Mediterranean coast of Andalusia. The authors proposed a method of spatial analysis of the flood risk associated with each sea-level rise scenario, using a DEM of 5m spatial resolution. For the evaluation of the exposure and vulnerability of the built-up area, especially for residential areas, data from the national cadastre have been used. The superposition of the set of cadastral parcels and the flood risk maps made it possible to identify the exposure of the cadastral parcels for residential use for each chosen scenario. And using the most pessimistic scenario, the exposed parcels amount to more than 24,000 and more than 13,000 exposed residential cadastral parcels were identified for which their risks, exposure, and vulnerability were calculated to finally assess the flood risk associated with future sea levels.

The last article in this monograph is dedicated to the island of Mallorca. In it, M. Grimalt-Gelabert, J. Bauzà-Llinás, and M.C. Genovart-Rapado analyze "The flood of October 9, 2018, in the city center of Sant Llorenç des Cardassar (Mallorca)". This population, unfortunately, has suffered since the 1940s, repeated episodes of flooding from the different tributaries of the Ca n'Amer torrent, but in 2018 the most important flood of the series occurred, which caused a large part of the population to be affected, including fatalities. The authors have analyzed the historical relationship of the town with the flooding processes, the response to them by the administration and the natural geographic environment and anthropic actions on the territory. In this work, the direct observation, the face-to-face, and graphic testimonies, and the fieldwork are to be highlighted. A detailed investigation of flows, directions, and levels has also been carried out, and exhaustive mapping of the event has been carried out, showing the sequential development of the flood. As a conclusion, it is indicated that the flood is the result of the combination of extremely important flows, natural processes of cutting in meanders, and angular sections that are combined with infrastructures that interfere with the flow of water and prevent its reintegration into the main channel. The administrative response to the floods has been the construction of artificial cemented canals, however, the canals have always been designed with a lower capacity than the registered floods. The canals have been supplemented with extremely solidly constructed, narrow-stem bridges, which has made overflows and flooding worse.

Finally, I would like to thank the editors of *Cuadernos de Investigación Geográfica* for offering to be the guest editor of this monographic issue. I also want to comment that after the proposal that I made to several authors to contribute their research to achieve a high-quality number, I have to say that the positive response was practically unanimous.

Due to the contents, results, and conclusions so interesting that, on different aspects related to the floods in the Spanish Mediterranean, which can be found in each of the articles presented here, a detailed reading is highly recommended. Our gratitude to all the authors who have contributed to this special issue of *Cuadernos de Investigación Geográfica* sees the light, both for their time and effort and for the extraordinary work they have done.

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FLOODS EVOLUTION IN THE MEDITERRANEAN REGION IN A CONTEXT OF CLIMATE AND ENVIRONMENTAL CHANGE

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ABSTRACT. Floods are the most important risk in the Mediterranean region, both due to their frequency and impact. Studies of historical floods show flood-rich periods that could be associated with climate causes, but there is also a certain growing trend as a result of changes in land use and increased vulnerability. If climate scenarios point to an increase in the torrentiality of precipitation, with longer dry periods and more intense rainfall, there is still a high level of uncertainty in their impact in floods. This paper addresses this issue, also considering the complex role of changes to hazards, vulnerability, exposure and capacity. It presents a synthesis of the state of the art, with particular incidence in the first results of MedECC and the most recent bibliography on floods trend. Conclusions show that floods in this region are mainly consequence of flash-flood events. A common positive trend of flash floods in the past probably due to land use changes and the occupation of flood-prone areas has been found (high confidence). The increase of convective precipitation could also justify this positive trend in the most recent period, in some regions (low confidence). Vulnerabilities to water related hazards are expected to be influenced by the future socio-economic conditions at the regional scale (medium confidence). Although expected changes in flood risks are not univocal, nor evenly distributed, flood impacts will increase in the entire Mediterranean region, mainly as a consequence of global changes in the catchments (land use, vulnerability, exposure), joined in the Northern part of the basin to the increase of heavy rainfalls (medium confidence).

Evolución de las inundaciones en la región mediterránea en un contexto de cambio climático y ambiental

RESUMEN. Las inundaciones son el mayor riesgo de la región mediterránea debido tanto a su frecuencia como a su impacto. Estudios de inundaciones históricas ponen de manifiesto que los periodos con un mayor número de inundaciones podrían estar asociados a causas climáticas, pero hay también una cierta tendencia a vincularlos a cambios en los usos del suelo y a un incremento de la vulnerabilidad. Si los escenarios climáticos apuntan a un incremento de la torrencialidad de las precipitaciones, con periodos secos más prolongados y lluvias más intensas, hay todavía un elevado nivel de incertidumbre en su impacto sobre las inundaciones. Este trabajo aborda esta temática, considerando también el complejo papel de los cambios en los riesgos, vulnerabilidad, exposición y capacidad. Se presenta una síntesis del estado del arte, con particular incidencia en los primeros resultados del MedECC y la más reciente bibliografía sobre las tendencias de las inundaciones. Las conclusiones muestran que las inundaciones en esta región son consecuencia principalmente de eventos de flash-flood. Se ha encontrado una tendencia positiva (nivel de confianza alto) de flash-floods en el pasado probablemente debido a cambios de usos del suelo y a la ocupación de espacios proclives a las inundaciones. El incremento de la precipitación convectiva también podría justificar esta tendencia positiva en los tiempos más recientes, especialmente en algunas regiones (confianza baja). Se espera que las vulnerabilidades a los riesgos relacionados con el agua se vean influidas por las condiciones socioeconómicas futuras a escala regional (confianza media). Aunque los cambios esperados en los riesgos de inundaciones no son unívocos, ni están distribuidos uniformemente, los impactos de las inundaciones aumentarán en toda la región mediterránea, principalmente como consecuencia de los cambios globales en las

cuencas (uso del suelo, vulnerabilidad, exposición) y el incremento de las precipitaciones intensas en el sector norte de la cuenca.

Key words: Floods, flash floods, climate change, natural hazards, Mediterranean region.

Palabras clave: Inundaciones, inundaciones súbitas, cambio climático, riesgos naturales, región mediterránea.

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1. Introduction

Floods are the natural risk with the greatest impact in the world both because of their frequency and the socioeconomic and environmental losses they produce, as in many cases they are linked to other phenomena such as landslides and/or severe weather. Over the 1997-2017 period, floods affected 76 million people in the world (UNDRR, 2020). The recent MEFF database (flood-related fatalities in the Mediterranean basin) shows that between 1980 and 2018, 1809 fatalities were recorded across six Mediterranean regions (Fig. 1); for the whole Mediterranean basin, the mean annual fatality rate is 0.5 fatalities per million inhabitants (Vinet *et al.,* 2019)

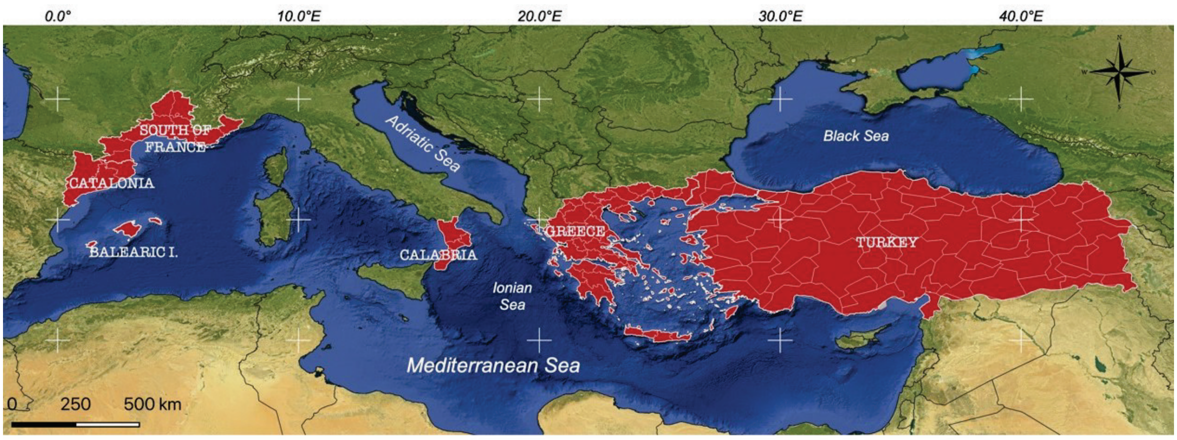

Figure 1. The Mediterranean Region and the countries/regions that are considered in the MEFF v2 database (from Vinet et al.*, 2019).*

There are multiple factors that can influence these impacts, from the characteristics of the rainfall or water flow, to the available means of evacuating the population and raising awareness. For this reason, we need to better understand the main drivers behind flood changes and the links between floods and climate and other factors (Merz *et al.,* 2012). Besides these aspects, which will be presented in the following chapters, the processes are not lineal and there are numerous related elements. For instance, initial soil moisture conditions prior to flood events play a key role in causing floods. An increase in rainfall intensity does not necessarily result in an increased flood risk because the runoff coefficient can be very variable over time and space due to complex interactions between precipitation and infiltration processes (Tramblay *et al.,* 2019). The type of soil can also have different sensitivity to changing climatic conditions (Camici *et al*., 2017; Piras *et al.,* 2016). At the same time, the size and orography of the catchment have a strong influence on changes due to climate and use of soil (Hall *et al.,* 2014).

Floods in the Mediterranean have the added complexity that they normally occur in small, ungauged basins in densely populated areas. This is important both when studying the frequency and magnitude of floods, and to improve early warning systems. In addition, they sometimes occur during periods of drought, and may go unnoticed in frequency studies. This paper focuses on the analysis of trends and anomalies in relation to floods in the Mediterranean. To better contextualize it, the article begins with a presentation of the study area and the factors that may be involved in flood risk. The main conclusions on climatic and environmental changes in the Mediterranean region that might be linked to floods, are shown afterwards. The following sections are devoted to trend and projection analysis, ending with the conclusions.

2. Study area

The Mediterranean region has specific characteristics that favour all kind of hydrometeorological risks (Fig.1). It is in an area where subtropical and polar air masses can converge, giving rise to severe weather and heavy rainfall. For instance, Insua-Costa *et al.* (2019) have demonstrated that the precipitable water mass during the October and November 1982 floods were mainly from the subtropical Atlantic and Western Mediterranean. In addition, the Mediterranean is a warm and almost closed sea, surrounded by an orography characterized by a notable mountainous relief, which favours cyclogenesis and an air mass with high humidity, instability and latent energy, with the consequent development of adverse weather events such as flash floods or strong wind storms (Jansà *et al.,* 2014). All of this makes weather forecasting, and therefore climate prediction, more complicated than usual. Beside this, the sociocultural and historical context is enormously heterogeneous, and the distribution of resources is very uneven. The North of the region presents greater well-being, economic development and governmental stability, while the South and the Middle East are characterized by rapid population growth, from about 105 million people in 1960 to more than 440 million in 2017. Climate change exacerbates all of these differences, even more so if one considers that a large number of the population currently lives in coastal areas, and it is expected that by 2050 this will reach 70% of the total.

Floods in the Mediterranean region are usually sudden, known in English as flash floods (Gaume *et al.,* 2016). The coastal and pre-littoral mountain ranges (Fig. 1) favour not only torrential rain concentrated in small basins, but also heavy rain. Although there is no single definition, a flash flood is one that occurs in a small catchment area (generally less than 1000 km^2) within 6 hours or less of the causative event (heavy rain, dam breach, levee failure, rapid thaw, or glacier floods) and often within 2 hours of the onset of high intensity rainfall (see www.nws.noaa.gov). Flash floods are generally caused by heavy rains that can be localised, affecting just one or two basins, or more widespread, producing flash floods within the framework of a major flood event.

From a climatic perspective, convective rains generally occur in summer and early autumn, because they are favoured by low-level instability and high temperatures (Llasat *et al.,* 2016a; Papagiannaki *et al.,* 2013). In the Mediterranean region, summer events are often local and short-lived, while in autumn the warmer sea surface temperature, as well as the large number of cyclones and organized weather disturbances, can lead to catastrophic events.

3. Methods and materials

This article presents the most recent findings on the evolution of floods in the Mediterranean region and the possible impact of climate change. This means that it is a review paper. To compile this paper, the main studies published on flood trends in the last decade have been taken into account, which have been synthesized, for the most part, in the First Report on Climate and Environmental Change of the Mediterranean (First Mediterranean Assessment Report, MAR1) carried out by the network of Mediterranean Experts on Climate and Environmental Climate Change (MedECC).Today MedECC is made up of more than 600 scientists from the fields of climatology, hydrology, biology, oceanography, social sciences, etc. From them, 85 scientists from 19 countries took part in this MAR1 report (MedECC, 2020). The impact of MAR1 was already evident in the previous report (MedECC, 2019) presented at COP-24 and at the 4th Meeting of Foreign Ministers of the Union for the Mediterranean held in Barcelona in October 2019. It also constitutes the basis of the 6th AR of IPCC Cross-Chapter Paper 4: Mediterranean Region. The present contribution includes the most important results of the MedECC (2019) report and the paper by Cramer *et al.* (2018).

Other recent publications focused on flood trends and flood variability in the Mediterranean region have been also considered. This focus on flood variability justifies why not all the articles on floods in the Mediterranean have been included here, since they constitute an unapproachable base. As an example, we could refer to Gaume *et al.* (2016) that offers a broad perspective on Mediterranean extreme floods and flash floods. But there are also papers that present flood databases, such as those by Gil-Guirado *et al.* (2016) and Llasat *et al.* (2014); other papers are mainly focused on the analysis of events such as those referring to the flash floods recorded in Genoa in 2014 (Hally *et al.,* 2015); other works are focused on the analysis of the social impact of floods (ex. Papagiannaki *et al.,* 2013); finally, we cannot forget those focused on the aspects of hydrometeorological modelling, either by applying hydrological models (ex. Braud *et al.,* 2010) or mesoscale meteorological models (ex. Martín *et al.,* 2007).

It must also be considered that most of the floods in this region are flash floods and coastal floods; riverine flooding is less frequent and ice jam flooding usually do not occur. Urban floods and surface water floods (Cortès *et al.,* 2018) are also included here.

4. Main factors involved in flood risk

The United Nations Office for Disaster Risk Reduction (UNDRR) recently published a Technical Review Report on hazard definitions that support the three landmark agreements adopted by the United Nations in 2015: the Sendai Framework for Disaster Risk Reduction 2015-2030, the Sustainable Development Goals in the 2030 Agenda, and the Paris Agreement on Climate Change (UNDRR, 2020). This report assumes the definition of 'hazard' adopted by the United Nations General Assembly (UNGA) in February 2017; namely, "a process, phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation". Consequently, to consider a phenomenon as a hazard, it needs to fulfil each of three criteria: has the potential to impact a community; has measurable spatial and temporal components; proactive and reactive measures are available. This definition excludes complex human activities and processes where it is difficult to identify a single or limited set of hazards, compound and cascading hazards, and underlying disaster risk drivers such as climate change. On the other hand, floods are considered a hydrometeorological hazard. The UNISDR (2009) defined a hydrometeorological hazard as the process or phenomenon of atmospheric, hydrological or oceanographic nature that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage. Figure 2 shows the different categories of hazards, while Figure 3 shows the different types of hydrometeorological hazards. A total of 318 hazards were reported by countries in 2019 as part of the Sendai Framework Monitor, of which the majority corresponded to hydrometeorological hazards–a total of 120. However, a large number of them were the same, with different denominations according the country. Figure 3 shows the most important ones. They have been classified according to the drivers, those that have an exclusively atmospheric origin (meteorological or climatological, like heavy rain), a mixed origin between atmospheric factors and other hydrological or geological factors, and a non-atmospheric origin. Floods are a mixed hydrometeorological hazard and is possible to distinguish between four types. The UNISDR (2009) introduced the concept of socio-natural hazards as the phenomenon increased in occurrence due to land and environmental degradation and included floods among them.

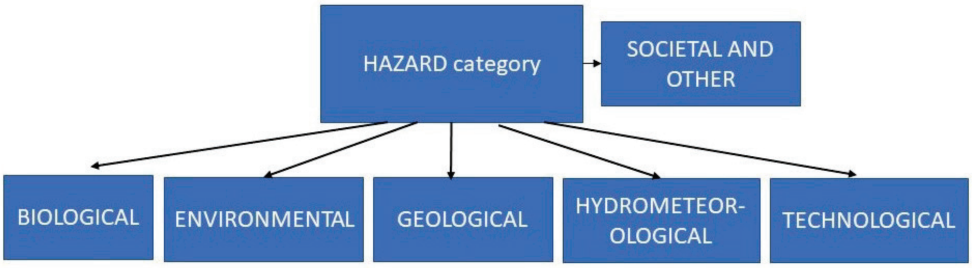

Figure 2. Types of hazards following UNDRR (2020).

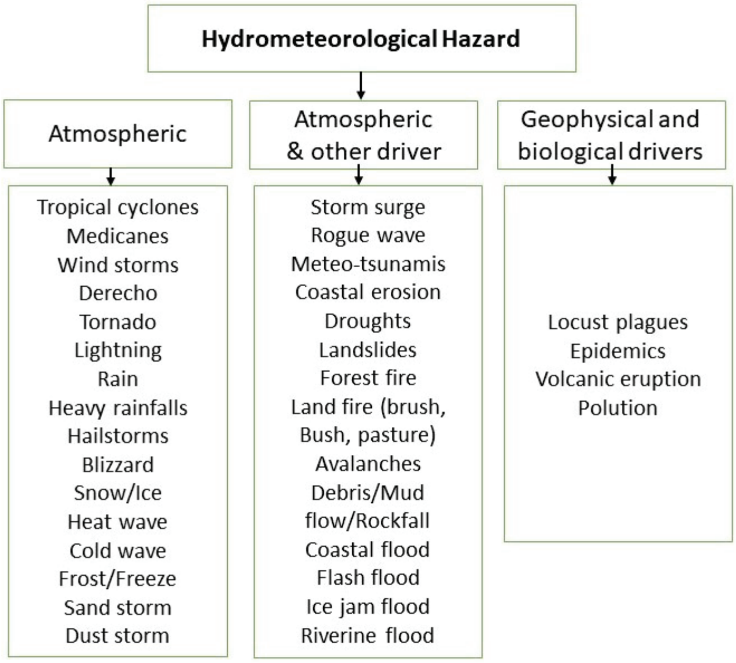

Figure 3. Main hydrometeorological hazards.

In 2009, the UNISDR (United Nations International Strategy for Disaster Reduction) defined risk as the combination of the probability of an event and its negative consequences (UNISDR, 2009). This definition was transferred to Eq. 1, where hazard (H) would include the probability of an event of determined characteristics (i.e. rainfall intensity) and vulnerability (V) would refer to potential negative consequences and usually also included exposure and risk management (Llasat *et al.,* 2009) (Eq.1). The UNISDR (2009) defined vulnerability as *the characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard*, and included in it factors such as the poor design and construction of buildings, inadequate protection of assets, lack of public information and awareness, limited official recognition of risks and preparedness measures, and disregard for wise environmental management. This kind of definition has been widely used to build risk maps as the combination of hazard maps and vulnerability factors. It has the advantage that allows the use of a colour code based on a matrix that combines hazard and vulnerability. In this case, flood hazard maps would show the potential flooded area for a given return period, while the vulnerability factors would include the type of building in the flooded area and its purpose of use (school, hospital, etc.). Floods are a natural hazard but not a natural disaster, because disasters are not “natural” due to their relationship with non-natural aspects like vulnerability.

$$R=H \times V \qquad \text{(Eq.1)}$$

However, different scientific communities distinguish exposure as a differentiating factor. In the GAR report (2019), the UN defined risk as the combination of hazard, exposure and vulnerability (Eq. 2).

$$R=H \times V \times E \qquad \text{(Eq.2)}$$

The recent report by the UNDRR (2020) modifies the preceding definitions and gives special importance to the capacity of the community to cope with risk and recover, which is nowadays known as resilience. The UNDRR (2020) state that *Hazards together with vulnerability, exposure and capacity, all contribute to disaster risk.* Following this statement, the risk equation would be Eq. 3

$$R=H \times V \times E \times C \qquad \text{(Eq.3)}$$

Considering Eq. 3, flood risk can change as a consequence of changes in hazard, vulnerability, exposure and coping capacity. In relation to floods, climate change can have an impact on the hazard, and environmental change can have an impact in vulnerability but also in flood hazard. National and regional plans devoted to adaptation to climate change usually refer to risk mitigation in order to diminish risk exposure and improve capacity. Nowadays the three equations coexist, and the most useful one to avoid confusion is the use of indicators for different variables. For instance, Aroca-Jiménez *et al.* (2018) propose an Integrated Economic Vulnerability Index (IEVI) for urban areas, which essentially considers three components: 1) Exposure (potential damage caused in areas prone to flooding, and potential damage at an individual level); 2) Sensitivity (level of wealth and economic capacity of urban areas to cope with the consequences of floods); 3) Resilience (ability of citizens to cope with the consequences of flash floods).

Another type of indicator is the impact on human lives. Petrucci *et al.* (2019) have published the EUFF (European Flood Fatalities) database, which contains all the people who have died as a result of the floods in some regions of Europe, most of them in the Mediterranean (Czech Republic, Israel, Italy, Turkey, Greece, Portugal, southern France, Catalonia and the Balearic Islands) for the 1980-2018 period. This work identifies 812 fatal floods with 2466 deaths, so, on average, each event killed 3 people. The probability of dying during a flood depends essentially on the physical parameters that characterize the hazard (i.e. the speed of the water, the height of the water level and the turbidity of the water), vulnerability (i.e. the construction characteristics of the house), exposure (i.e. if the victim is in a flood-prone area), and the human-flood interaction (i.e. whether the victim has responded correctly to early warnings).

The number of casualties as a consequence of floods, as well as the economic damages, provide integrated information on the flood risk disaster, and it is difficult to distinguish between the weight of each factor in Eq.3. On the other hand, when floods are only estimated from a discharge threshold, we are working from a flood hazard approach. Both approaches are used interchangeably in the literature, which can create confusion. Added to this is the lack of homogeneity of the series, their short duration, and the poor spatial representation, since many floods are due to local rainfall. This leads to different authors reaching contradictory conclusions. In the following chapters it will be necessary to keep these considerations in mind. Given that what we are dealing with here is the variation of floods in a context of climate change, we will begin by presenting the most relevant conclusions about the Mediterranean region.

5. Main environmental and climate changes in the Mediterranean Region

The article by Cramer *et al.* (2018) shows that the Mediterranean region has warmed 1.4ºC compared to the pre-industrial period (about 0.03ºC/year), which is 20% more than the global average (Fig. 4). The greatest increases in temperature are recorded in the summer, accompanied by a higher frequency of heat waves and tropical nights (the minimum temperature does not drop below 20ºC). There is a longer duration of consecutive days without rain throughout the region, in addition to an increase in droughts. The temperature of the Mediterranean Sea has increased by about 0.4ºC/decade between 1985 and 2006, increasing more in the East (about 0.5ºC/decade) than in the West (about 0.3ºC/decade). Recently, Pastor et al. (2020) have showed that Sea Surface Temperature (SST) of the Mediterranean has increase 1.3ºC between 1982 and 2019. This warming is greatest in May, June and July. The oceans absorb 30% of anthropogenic carbon dioxide, increasing its acidity and damaging marine ecosystems. A decrease in pH of 0.1 has been observed and it is estimated that levels will continue to decrease by 0.018 and 0.028 per decade.

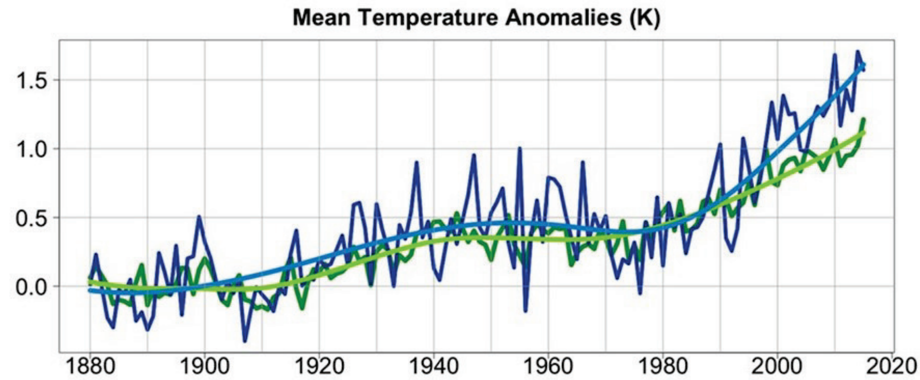

Figure 4. Increase of the annual temperature anomaly in comparison with the period 1880-1899 (green: world average; blue: Mediterranean region) (from Cramer et al.*, 2018).*

As a result of global warming, the level of the Mediterranean Sea rose 1.1 mm/year between 1970 and 2006, which is being aggravated by the loss of ice from Antarctica and Greenland. Terrestrial ecosystems suffer from the loss of biodiversity both due to climate change and changes in land use, overexploitation and pollution. The abandonment of agricultural practices and livestock grazing areas, especially in the North, is one of the main causes, exacerbated by an increase in forest areas prone to fire. It should be said, however, that burned areas show a downward trend in the Mediterranean region, except for some areas in Sicily or Portugal, due to improved fire prevention and extinction. Even so, the scenarios point to an increase close to 40% with an increase of 1.5ºC, and more than 100% if the increase reaches 3ºC (Turco *et al.,* 2018).

Without mitigation measures, temperatures will increase by 2.2ºC in 2040 and will exceed 3.8ºC in some subregions by 2100, aggravated by the urban heat island effect in cities, which increase these temperatures by around 4ºC. For many of the large cities in the MENA region (North Africa and Eastern Mediterranean) the coolest summer will be warmer than the coldest summer month at the present. For each degree that the temperature increases, precipitation will decrease by around 4%, especially in the South. For more than 2ºC, in some regions it may decrease by 30% (i.e. Turkey), and the frost season may even disappear (i.e. in the Balkans).

The models show an increase in heavy rains in the North, which is precisely the region most affected by floods, while in the South heavy rains are expected to decrease. On the other hand, extreme droughts will be more frequent than at present. The increase in the duration of these dry spells is expected to be 7% for an increase of 1.5ºC. At 2ºC it is calculated that the fresh water available for consumption may decrease by between 2% and 15%, which, together with an increase in demand due to population growth (between 22% and 74%), and a decrease in underground resources, both in terms of quality and quantity, may result in some 250 million people being water poor over the next 20 years (less than 1000 m^3/year), with the greatest shortage in the East and South. In addition, an increase of between 4% and 18% in terms of water needs for irrigation is expected (this constitutes between 50% and 90% of the total demand).

Depending on emission scenarios, it is calculated that the temperature of the Mediterranean Sea may increase by between 1.8ºC and 3.5ºC in 2100. Acidification and the increase in sea temperature would lead to the loss of 41% of marine predators (including mammals), and an increase in the intensity and extent of jellyfish colonies, as well as the invasion of more than 700 non-native species (plants and animals) including predators such as lionfish, most from the Red Sea, which would cause greater losses in the native habitat. It should be added that overfishing has led to the loss of 34% of fish species. By 2100 the sea level could have risen between 52 and 190 cm. The impacts of these changes are very serious, since a third of the population lives in coastal regions, with more than 37 million people living in coastal areas in North Africa. By 2050, it is expected that half of the 20 cities in the world that will most suffer from rising sea levels are in the Mediterranean. These impacts include, among others, coastal erosion and damage to infrastructure on the coast, increased saline intrusion and coastal flooding, and the loss of beaches, agricultural areas and marshes.

6. Trends

The high increase in temperature and sea levels presented in the previous section could have several effects on floods:

- An increase in evapotranspiration and therefore in the mass of precipitable water in the atmosphere.
- An increase in atmospheric instability.
- An advance in the thaw season that would cause an increase in water flow at unusual times.
- A decrease in discharge due to evaporative loss.
- A decrease in soil humidity.

However, one of the key messages of MedECC (2019) is that past trends for precipitation are not so robust in quantity and magnitude, since internal climate variability limits our capability to detect long-term trends. In the same way, there is not a common sign pointing to an increase in floods. The special report on extremes by the IPCC (2012) stated that *it is likely there has been a worldwide increase in extreme high-water events during the late 20th century, with a likely anthropogenic influence on it.* The AR5 of IPCC (2014) and the IPCC SR1.5 (IPCC, 2018) also conclude that *there is "limited to medium" evidence available to assess climate-induced changes in the magnitude and frequency of floods on a regional scale, with evidence of "low agreement" and "low confidence" on a global scale to detect these,* but, despite this absence of changes in flood occurrence or magnitude, there is an increase in flood losses due to an increase in exposure and vulnerability to floods ("medium confidence").

Consequently, when discussing flood trends and trying to associate the cause with the effect, a very cautious position must be taken (Merz *et al.,* 2012; Hall *et al.,* 2014). The main sources of uncertainty or even, in some cases, of confusion, are the following:

- The strong variability of rainfall in the Mediterranean region (affects the hazard).
- Ignorance of some of the factors responsible for heavy rains (hazard).

- The influence of environmental changes in the catchments (hazard).
- Changes in the basin either in terms of land use or hydraulic infrastructures (Merz *et al.,* 2012; Hall *et al.,* 2014) (can affect the hazard and vulnerability).
- Changes in exposure, response capacity, early warning, etc. (Kreibich *et al.,* 2017).
- The semantic confusion that sometimes exists between heavy rains and floods (hazard).
- The concept of flooding. From a "top-down" perspective, an extreme value of flow is usually understood as such, regardless of whether there are impacts or not. In turn, the concept of extreme can be quantified in numerous ways (return periods, exceeding thresholds, etc.) (i.e. Blösch *et al.,* 2019). If the perspective is "bottom-up", it is usually based on the information about the damage produced, without taking into account the frequency of the event. In this case, the selection criteria can be very different, completely affecting the sample analysed (Llasat *et al.,* 2013b) (affects flood risk estimation).
- The length, homogeneity and period comprised by the series analysed (Llasat *et al.,* 2013b) (affects flood risk trend estimation).
- The reliability of the measurements and observations, as well as the quality and continuity of the information (Llasat *et al.,* 2013b) (affects the flood risk trend estimation).
- The event quantification methodology that can refer to the basin or region as a whole, to all the points for which the impact is recorded, or the total hydrometeorological episode (see, for example, the difference between the criteria of Barriendos *et al.,* 2003, where they count the number of floods from the affected localities, and Llasat *et al.,* 2013b, in which they count the episodes)

In the synthesis that is presented below, there does not have to be an agreement between authors, or even for the same author in different contexts, so whenever it was possible to find out, what is understood by flood, the period to which it refers, etc., is given in brackets.

6.1. Secular changes

A study recently published in Nature (Blösch *et al.,* 2020) shows the compilation and analysis of all historical flood series in Europe from 1500 to 2016, taking data from archives, the press, etc. In order to homogenize the information, all the texts were placed in their respective historical contexts with meticulous attention to detail in order to make them comparable. This allowed for a regionalization to be created, identifying nine flood-rich periods. Notable periods include 1560-1580 (western and central Europe), 1760-1800 (most of Europe), 1840-1870 (western and southern Europe), and 1990-2016 (western and central Europe). Comparisons of air temperature reconstructions show that these historical flood periods were substantially colder than the intermediate phases, which appears to contradict the observation that, in some areas, such as north-western Europe, the recent warmer weather is linked with major flooding. The article therefore argues that the underlying mechanisms may have changed and that the hydrological conditions of the present are very different from those of the past. This is compounded by a change in seasonal distribution: previously, 41% of floods in Central Europe occurred in the summer, compared to 55% today. These changes could be related to changes in precipitation, evaporation and thaw, constituting an important indicator to distinguish the role of climate change from other control factors such as deforestation and river management.

The secular variation of floods in the northwest Mediterranean region has already been analysed in the SPHERE project (Benito *et al.,* 2004). On the one hand, a positive trend was obtained from the episodes considered as extraordinary (floods that caused significant damage, but not total destruction of bridges, buildings or mills) from the end of the 19th century, which was mostly linked to changes in land use (Fig. 5). On the other hand, anomalous periods of catastrophic floods (with total destruction of infrastructure) were identified, mainly concentrated around the Little Ice Age (Barriendos *et al.,* 2003; Llasat *et al.,* 2005), which would be in line with the observations of Blösch *et al.* (2020). The detailed analysis of the so-called Maldá Oscillation, characterized by the high number of floods between 1760 and 1800 (Fig. 6), showed an anomaly in the NAO index (Barriendos and Llasat, 2003) linked to atmospheric circulation in the north Atlantic. Barrera-Escoda and Llasat (2015) extended the series to 1301-2012 and analysed not only the relationship with the NAO but also with solar activity, finding a significant negative correlation (-0.42 for the autumn season). From a physical point of view, the most recent explanations focus on the influence of the heating and cooling of regions of the stratosphere with the consequent impact on the tropospheric circulation, giving weight to possible teleconnections, such as the NAO (Ermolli *et al.,* 2013). In turn, the synoptic-scale circulation will give some types of weather that may favour the development of intense rains, which are the main cause of floods in the Mediterranean, such as the presence of synoptic or mesoscale lows (Gilabert and Llasat, 2017, Jansà *et al.,* 2014). These results are consistent with the studies that are currently being carried out to find the sources of water vapour that feed the intense rains in the Mediterranean and that demonstrate the notable role of sources of Atlantic origin, against the existing perception that most came from the Mediterranean (Insua-Costa *et al.,* 2019). In this context, the latest flood episodes that have affected the Spanish Mediterranean coast would be a call for reflection, given the influence that the Greenland thaw has on large-scale climate variability over the Mediterranean basin, partially associated with circulation patterns such as the Arctic Oscillation (AO) and the North Atlantic Oscillation (NAO), which control part of the moisture fluxes over the western and eastern Mediterranean basins (Tramblay and Hertig, 2018).

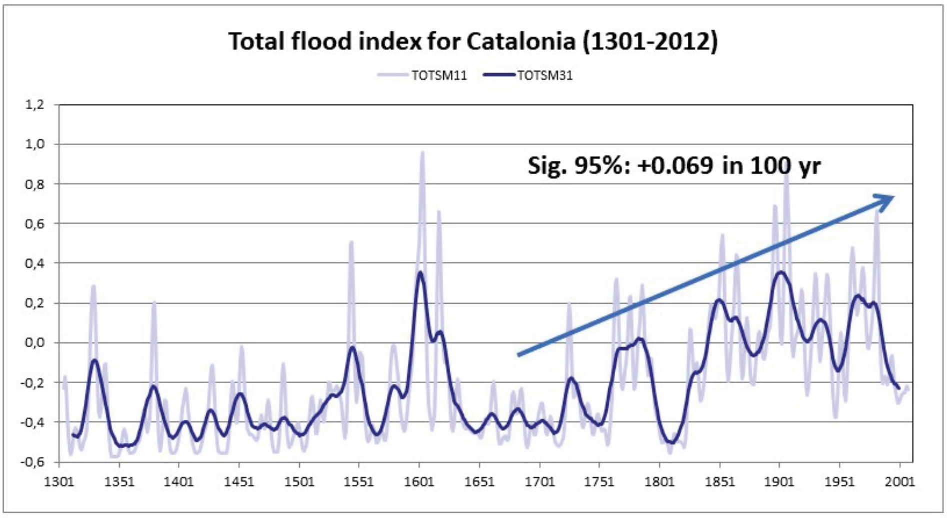

Figure 5. Floods evolution in Catalonia since the 14th century. The positive trend is due to the extraordinary floods (from Barrera-Escoda and Llasat, 2015).

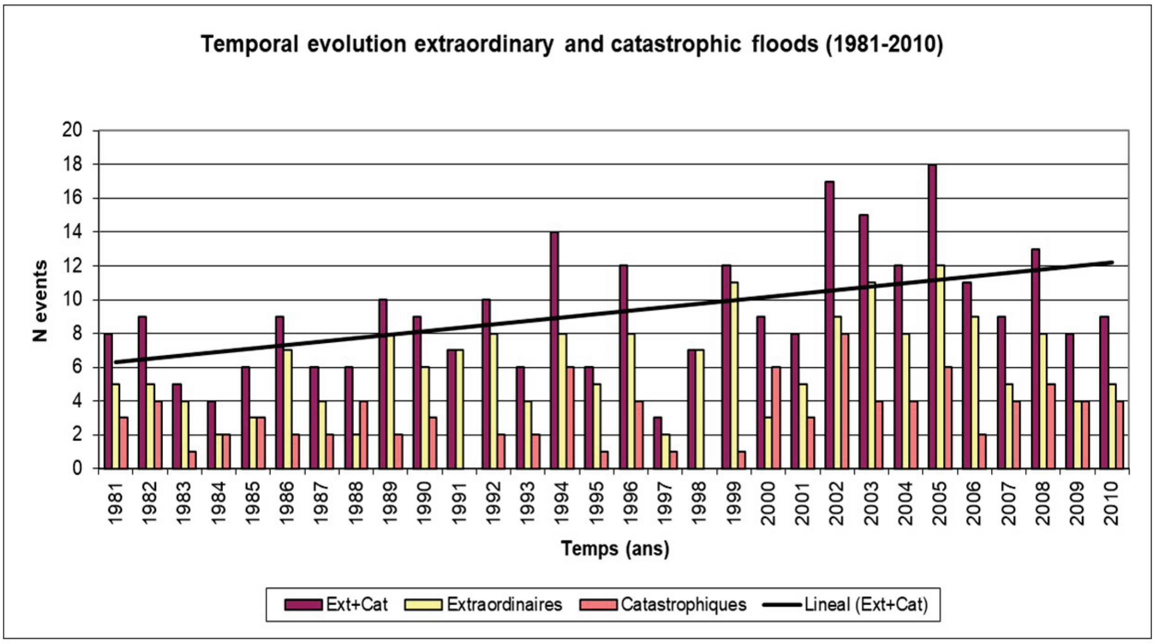

Figure 6. Temporal evolution of total floods recorded in Catalonia and the Balearic Islands (Spain), southern France, and Calabria (Italy). The category in basis to the damages produced is distinguished (catastrophic have worse impacts than extraordinary), (from Llasat et al.*, 2013a).*

6.2. Recent changes

When we expand the temporal resolution and bring the scale closer to current times, the influence of other non-climatic factors takes on greater prominence. An example of a detailed work that analyses changes in precipitation, river discharge and uses of soil is the one by Tramblay *et al.* (2019). They analysed 171 daily discharge data series with a median record length of 45 years (minimum of 20 years of daily discharge data), in southern France, besides other hydrometeorological outputs obtained from the SAFRAN reanalysis (Quintana-Seguí *et al.,* 2008) and the ISBA land surface model (Habets *et al.* 2008), as well as the evolution of land cover using the CORINE database between 1990 and 2018. Floods are estimated using two different percentiles: moderate floods (above the 95th percentile of daily runoff in all stations) and more severe floods (above the 99th percentile). The trends in floods between 1958 and 2018 are detected by a corrected Mann-Kendall test (to avoid the effect of serial correlation, Sen, 1968). To estimate the magnitude of the temporal trend, the quantile regression method was applied (Koenker and Basset, 1978). They found that the intensity of the most extreme floods shows significant upward trends in only a few basins, while most trends are towards fewer annual floods, which they associate to a reduction in soil moisture as a consequence of increased temperatures and a decrease in evapotranspiration and precipitation. In general, the larger catchments show significant downward trends in flood occurrence, and forest areas show more negative trends than agricultural catchments. An increase of up to 20% and 36% in urban areas and discontinuous urban fabric, respectively, can have a strong impact on runoff generation due to an increase in impervious surfaces. In urban catchments with a lower increase in urbanization, trends are negative, while for the rest of them no trends were found. The work of Tramblay *et al.* (2019) shows that with the same large-scale climatic drivers (in terms of temperature, evapotranspiration and precipitation), the flood trends in the basins can differ, even for neighbouring basins, as a consequence of other factors like topography, soil and land cover combinations.

A similar study was carried out for the Barcelona Metropolitan Area (Llasat *et al.,* 2016b). As all of the floods in the area (mainly surface water floods and urban floods) were due to heavy rainfalls, the contribution explored the evolution of land use, population, precipitation and coping capacity. The results confirmed the strong role played by the increase in urban surfaces and impermeable soil (like the new airport) which gave rise to an increase in extraordinary floods, despite the fact that maximum precipitation showed no increase, with the exception of Barcelona. This city was recognized by the UNDRR as a resilient city to floods, due to the implementation of early warning systems and rainwater tanks (Nakamura and Llasat, 2017)

While most studies agree that flood damage is increasing (Barredo *et al.,* 2012, CRED-UNISDR, 2015), observations point to the opposite in some regions. In Spain and southern France, generally decreasing trends have been found in maximum annual flows (Mediero *et al.,* 2014; Renard *et al.,* 2008). The attribution of these negative trends could be related to the increase in forested areas in the upper part of the river basins because of a decrease in cultivated areas (Hall *et al.,* 2014). For the Po river (Italy), a clear trend is not observed in terms of annual maximum floods (Montanari, 2012). In contrast, Greece has seen an increase in the frequency of floods in recent decades (Diakakis, 2014). For the Mediterranean basins, Mangini *et al.* (2018) shows a trend towards an increase in the magnitude of floods, but a decrease in frequency.

The analysis by Blöschl *et al.* (2019) from the most complete database of floods in Europe for the 1960-2010 period (understood as extremes of flow) shows a decreasing trend for the Mediterranean region in medium and large basins, mainly due to a decrease in precipitation and increased evaporation. In Spain in particular, the change in the average annual discharge of floods per decade would be between -5 and -12%. This divergence from observed trends in maximum flood discharge and damage may be associated with other parameters, such as exposure and vulnerability. In fact, Barredo *et al.* (2012) show that the increased economic impact of floods in Spain may be due, in part, to an increase in insured property and the cost of living. In the comparative analysis of pairs of events that occurred in the same region at two different times (for example, the episodes of 10 June, 2000, and 25 September, 1962, in Catalonia) and for different parts of the world, Kreibich *et al.* (2017) conclude that in general the impact of floods has decreased in the most economically developed countries, mainly due to changes in habits and behaviours, both due to general improvements in the cultural level of the population and improvements in preventive measures, the early warning system and emergency management, which is not an obstacle to an increase in the value of exposed assets.

In the case of Mediterranean countries, there is another important factor—most floods occur in ungauged torrential basins, mainly affecting the coast, where the population and urban settlements are increasing rapidly in flood-prone areas (Gaume *et al.,* 2016). Thus, a detailed and systematic analysis shows an increase in floods in regions of Italy, France and Spain for the 1981-2010 period (Llasat *et al.,* 2013a) (Fig. 6). This increase is not found when we refer to catastrophic floods (Fig. 7), as we have also observed in longer historical series (Barrera-Escoda and Llasat, 2015; Barriendos *et al.,* 2019), that are usually consequence of more organised convective systems in well-defined meteorological patterns. This positive and significant trend of 2,5 floods/decade would be mainly due to extraordinary floods, usually associated to local heavy rainfall events in non-gauged catchments, usually surrounded by very populated villages, as a consequence of an increase in vulnerability and exposure, despite improved coping capacities

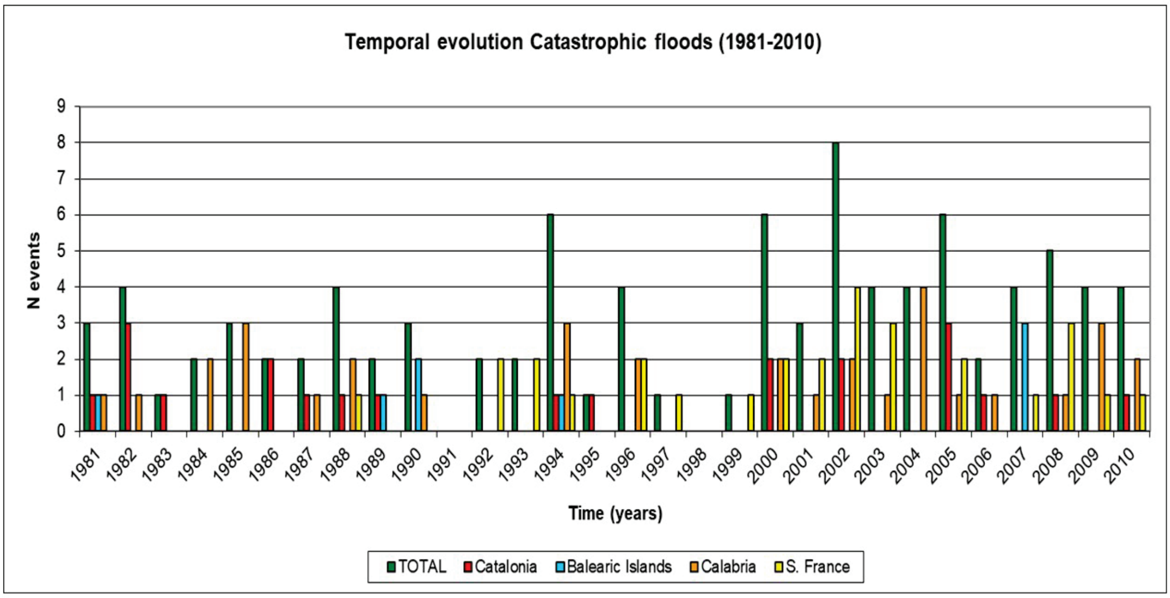

Figure 7. Temporal evolution of catastrophic floods recorded in Catalonia and the Balearic Islands (Spain), southern France, and Calabria (Italy), (from Llasat et al.*, 2013a).*

Regarding precipitation, no significant trend is observed in the upper extremes on a daily scale. However, Llasat *et al.* (2016a) found a small trend in the period 1996-2011, in north-east Spain, in the increase in convective precipitation concentrated in fewer events, which would be consistent with the increase in local flash floods. The analysis of 5-min precipitation series for a longer period (1989-2015) in the eastern and north-eastern part of the Iberian Peninsula corroborates this increase in convective precipitation, mainly in the coastal area and concludes, with medium confidence, that an increase in total and convective precipitation has been found in autumn, while a decrease in total precipitation but an increase in the convective contribution has been found in summer. Considering that convective precipitation can contribute with more than 30% to total precipitation and, in some months, with more than 90%, this trend is relevant (Llasat *et al.,* 2021). This strong role of convective precipitation that gives place to heavy rainfalls and flash floods can be explained by the orography surrounding the Mediterranean Sea, the high frequency of surface lows (Romero *et al.,* 1999; Jansà *et al.,* 2014) and the strong potential instability in low levels favored by a warm sea. Pastor *et al.* (2020) have found a continuous warming trend of 0,035ºC/y of SST for the entire Mediterranean, that means an accumulated change of 1,3ºC between 1982 and 2019, while Cramer *et al.* (2018) have observed an increase of 1ºC for the entire Mediterranean Region and the same period. This differential trend between SST and air temperature near surface would be indicating a worsening of the thermodynamic conditions favorable to convection.

6.3. Projections

The MedECC (2020) report concludes that due to alterations in general climate circulation, most climate simulations suggest reduced future precipitation associated with increased evaporation, leading to a decline in runoff. Despite the general drying which is expected to be associated with more prolonged and severe droughts, extreme rainfall will likely increase in the North of the basin but probably decrease in the South (Tramblay and Somot, 2018; Colmet-Daage *et al.,* 2018).

Most of the studies refer to precipitation projections, and there are hardly any studies that obtain flow projections. For the Mediterranean, the most famous study is by Alfieri *et al.* (2015). They apply the group of downscaled climate projections EURO-CORDEX (Coordinated Downscaling Experiment over Europe), forced by the RCP8.5 (Representative Concentration Pathway, 8.5Wm^2), to drive the distributed hydrological model Lisflood (Burek *et al.,* 2013) over extreme streamflow events (5 km^2 x5 km^2, daily step). Lisflood is the operational model adopted by the European Flood Awareness System (Thielen *et al.,* 2009). The results are expressed as relative changes from baseline scenarios (1970-2005). Data are aggregated over both time (2006-2035, 2036-2065, 2066-2095, and referred to as "2020", "2050", and "2080", respectively) and space (precipitation variables are aggregated over 22 European river basins with an upstream area at the outlet larger than 50,000 km^2). The Mann-Kendall test (Kendall, 1975; Mann, 1945) is performed to evaluate the statistical significance of the trends. Two selected discharge variables are extracted directly from the Lisflood model output (average streamflow Q, mean annual daily peak flow QMAX), while extreme values are obtained using the peak over threshold (POT) approach after fitting a Gumbel extreme value distribution using the L-moments approach (Hosking, 1990); they are the discharge peaks exceeding the return period of 2 years (performed on each grid point on the European river network), 100 years and 500 years (Q100 and Q500, aggregated at a river basin and country level). Following Alfieri *et al.* (2015), the climate projections agree on a 30% reduction in annual precipitation in southern European countries, particularly in the Iberian Peninsula, Greece and southern Italy. The average streamflow (Q) follows the same behaviour, with negative changes in southern Europe (i.e. lower than 40% in southern Spain) as a result of a reduction in annual precipitation and increased evapotranspiration. Although some rivers in southern Europe QMAX, Q100 and Q500 show significant positive trends by 2080 (i.e. the Ebro, Duero, Garonne, Po and Rhone rivers), in general they show a discontinuous pattern and some regions do not agree with the ensemble models. On the other hand, a reduction of peak discharges in the Guadalquivir basin (less precipitation and more evapotranspiration) is clear, and the events with a return period of 2 years will be less frequent in the future in the Guadiana and Guadalquivir rivers.

Cortès *et al.* (2019) show changes in the probability of flood damage in eastern Spain (specifically in the autonomous communities of Catalonia and Valencia) as a result of global warming of 1.5º, 2º and 3º C above pre-industrial levels and bearing in mind different population scenarios. The model uses a set of seven regional climate model simulations from the EURO-CORDEX project (Jacob *et al.,* 2014), and considers 5 different socioeconomic scenarios that include projections of population, urbanization and Gross Domestic Product on a global and national scale (O 'Neill *et al.,* 2014). The results point to an increase in the probability of an event with significant economic damage occurring, with greater increases with increased warming and when both climate change and population change are included. The study does not deal with flood projections but with precipitation on a daily scale, given the remarkable correlation observed between rain and flood impact, taking the 40 mm threshold as the indicative of the possibility of sudden flooding in small basins when such an amount is collected in a very short period of time.

7. Conclusions

Throughout this paper we have analysed floods in the Mediterranean in a context of climate and environmental change. In summary, the most notable conclusions are the following:

1. There is insufficient evidence that river floods are increasing in the Mediterranean.
2. There is a natural variability already detected in secular series that is still not completely explained.
3. Flash floods in small non-gauged basins are increasing due to increased vulnerability and exposure, but it seems that the hazard is also increasing in some zones due to more intense and concentrated rains in very short periods of time, together with the degradation of the basins.

4. A change in the hydrometeorological pattern is detected in the floods in Europe, which may be associated with both thermodynamic conditions that favour convection, and dynamics on a global scale.
5. Future projections point to an increase in heavy rains, especially in Mediterranean Europe, and an increase in the South of the Mediterranean.
6. Future projections show a decrease in flood hazards in some Mediterranean rivers (mainly in southern Spain) and an increase in others (i.e. the Ebro river) at the end of the 21st century.
7. Taking into account future rainfall and socioeconomic scenarios, the probability of high-impact flood events will increase as the temperature rises.
8. Due to the high spatial variability and the high degree of complexity in the relationships between the factors involved in flood risk, the use of integrated indices is proposed.
9. It is necessary to include variables that consider changes in climatic and socioeconomic conditions in flood damage analysis.
10. Flood management must be approached from an integrated and holistic point of view that includes improved risk awareness among the population and their participation in the formulation of mitigation strategies.

These strategies should bear in mind the Third World Conference for Disaster Risk Reduction of the United Nations and the agreements in the Sendai Framework (18 March 2015). These agreements can be summarized, in the floods case, in: reducing the global average mortality rate, the global average number of affected people, the direct economic loss and the damage to critical infrastructure and the disruption of basic services; and increase the number of countries with national and local flood risk reduction strategies, the international cooperation, the availability and the access to multi-hazard early warning, information and disaster risk assessment systems. These goals should be achieved by following the four priorities for action relatives to flood disaster risk: understanding, strengthening governance, investing to improve resilience, and improving disaster preparedness in terms of recovery, rehabilitation and reconstruction.

The Sendai Framework joined the 2007 EU Floods Directive (Directive 2007/60 / EC) offer a good flood risk management philosophy (Nakamura and Llasat, 2017). In the case of the Mediterranean, the projected increase in population on the coast, a flood-prone area, does not benefit compliance with the Sendai agreements. There is also a second and important problem centred on the differences between the European part, which is much more resilient, and the MENA region (North Africa and Mediterranean Asian countries), except for Israel, show fewer copying capacities. Although the climatic scenarios point to a greater increase in intense rains in the northern part, with major copying capacity, we cannot forget that the rise in sea level will also increase sea floods, and in this case, the African region can be very affected due to the proximity of agricultural areas to the sea (MedECC, 2020). The EU Floods Directive suggests the possibility of being transposed also to the other Mediterranean regions, taking advantage of the existence of the Union for Mediterranean created during the Barcelona Conference of 1995. Following the proposals of the Sendai Framework regarding international collaboration, the transfer of knowledge between experts could be improved and early warning systems could be shared. But this is only a reflection, a starting point for future multidisciplinary work and the necessary collaboration between scholars and policymakers.

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STRUCTURAL MEASURES AGAINST FLOODS ON THE SPANISH MEDITERRANEAN COAST. EVIDENCE FOR THE PERSISTENCE OF THE "ESCALATOR EFFECT"

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ABSTRACT. The risk of flooding on the Spanish Mediterranean coast is a constant threat whose importance has progressively increased in recent decades despite the enormous efforts made to mitigate it. Of the two strategies practiced to reduce the effects of this danger, structural measures have prevailed to a great degree over non-structural ones during this period of increased risk. Here, these works carried out from the beginning of the 20th century to the present are cataloged, with a double objective: (i) to show the evolution of the number of infrastructures, their typology, and their distribution on the Mediterranean coastline; and (ii) to evaluate whether the basins with and without a dam have followed differing trends in the occupation of floodplains to show the persistence of the "escalator effect". The results obtained indicate that there is no statistically significant difference between the occupation of the floodplainsby basins with and without a dam for the Return Periods (RP) 50, 100, and 500 years. However, for RP10, there is a higher occupation by basins with a dam.

Actuaciones estructurales contra inundaciones en el litoral mediterráneo español. Evidencias de la persistencia del "escalator effect"

RESUMEN. El riesgo de inundación en el litoral mediterráneo español es una constante cuya importancia ha ido aumentando progresivamente en las últimas décadas a pesar de los enormes esfuerzos realizados para mitigarlo. De las dos estrategias practicadas para reducir los efectos de este peligro, las acciones estructurales han prevalecido en gran medida sobre las no estructurales durante este período de mayor riesgo. En este trabajo se catalogan las actuaciones en funcionamiento con un doble objetivo: (i) mostrar la evolución del número de infraestructuras, su tipología y su distribución en el litoral mediterráneo; y (ii) evaluar si las cuencas con y sin presa han seguido diferentes tendencias en la ocupación de las llanuras aluviales para evidenciar la persistencia del "escalator effect". Los resultados obtenidos indican que no existe diferencia estadísticamente significativa entre la ocupación de las planicies aluviales por cuencas con y sin presa para los Períodos de Retorno (PR) 50, 100 y 500 años. Sin embargo, para PR10, hay una mayor ocupación por cuencas con presa.

Key words: Risk of flooding, structural measures, perception, escalator effect, Spain.

Palabras clave: Riesgo de inundación, actuaciones estructurales, percepción, "escalator effect", España.

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1. Introduction

The scientific approach and formulas against the hazards of flooding have evolved substantially in recent years, from a technocratic and applied position of responding to problems to a more social one. According to Smith and Petley (2009), four major stages can be seen that have marked the changes in the structural strategy. In the first place, until 1950, all the effort and attention were dedicated to the technological capacity, and the construction of large infrastructures was the only solution to mitigate natural hazards, especially those of hydrometeorological origin. This stage was followed by another of a behavioral nature in which, in the face of evidence of increased economic losses associated with disasters, emergency management gained ground. The third stage began in the 1970s. Some scientific studies (White, 1958, 1973; Montz and Gruntfest, 1986) show convincing results that reveal the limited effectiveness of structural measures to stop the increase in economic losses associated with the floods and the need to reflect on and reformulate the way to tackle the danger. Later work, such as that of Parker (1995), tried to respond to this trend and concluded that the false sense of security derived from said engineering measures would only have increased the risk exposure, since it encouraged the occupation of floodplains that until then had not been altered by humans. This social process has been given different names: escalator effect (Parker, 1995), paradox of safe development (Burby, 2006), or leveé effect (Lane *et al.,* 2011). A fourth stage commenced when we became aware of the above and prevention began to gain prominence in the scientific world, in the late 1980s and early 1990s, with the declaration of the International Decade for Natural Disaster Reduction proclaimed by the United Nations. Unfortunately, the measures taken by administrations are generally subject to delays and so floods force them to make use of specific measures such as channels and storm tanks installation.

The Spanish Mediterranean watersheds, the object of the present work, are a good example of the aforementioned process. Here, floods represent the most frequent danger of natural origin, due, to a great extent, to the impact of flash-flood episodes - such as those that have recently affected urbanized areas (Berz *et al.,* 2001; Jonkman, 2005). This should be more than enough evidence to realize that any strategy based on risk management and derived from technical measures to control danger will not be effective in reducing losses. However, the problem is more complex than it seems to be and, to a large extent, it is related to the degree of perception of hazard and the purpose of the measures already mentioned.

When a flood occurs with catastrophic results, the affected population immediately notices a lack of security and equally quickly demands structural measures to solve the problem. Historically, this situation has been increasingly repeated in societies where population pressure and urbanization positively correlate with the increase in floods, so much so that significant resources have been allocated with the intention of mitigating the risk of flooding. Examples of defense plans against flooding include the Segura Basin (southern Spain) (Lemeunier and Picazo, 1988), the diversion of the mouth of the Turia River as it passes through the city of Valencia (Spain), the Dutch embankment program (Wesselink, 2007), in Pakistan (Tariq and Van De Giesen, 2012), and those in the USA (Galloway, 2004).

Considering the trend of the losses caused by this type of episode (Gil-Guirado *et al.,* 2019), and regardless of their accentuation over time due to climate change (Quereda, 2000; Djalante, 2019), solutions based on structural measures seem to be insufficient since the exposure to the flooding hazard has not stopped growing (Pérez-Morales, 2008; Pérez-Morales *et al.,* 2015; López-Martínez *et al.,* 2020). Works on the subject (Saurí *et al.,* 2001; Calvo García-Tornel and Granell Pérez, 2009; Saurí *et al.,* 2010) seem to reach the same conclusion as Parker regarding this cognitive dissonance. That is, the construction of a dam has the same effect on the perception of the population as the temporal distancing of a flood episode; thus, the danger is apparently obviated or considered controlled, with the consequent reckless management response and the occupation of areas bordering the riverbed, reinforced by the false sense of security generated by said infrastructures. The foregoing leads us to question whether a similar trend has truly been experienced in our study area and, indirectly, if there is a different perception among the population that occupies those basins without a dam, with respect to those that do have a dam, to determine if the "escalator effect" suggested by Parker and Tapsell (2009) persists.

Based on all the above, the objectives proposed for this work were the following: (i) to catalog, geolocate, and date the structural measures aimed at mitigating the risk of flooding on the Spanish Mediterranean coast that are working, and (ii) to determine if a significant difference exists between the hydrographic basins regulated by dams and those that are not, in the trend followed in the occupation of floodplains from the construction of a dam to the present.

2. Study area

The study area includes the basins and sub-basins that drain the municipalities of the Spanish Mediterranean coast between the Region of Murcia and Catalonia (Fig. 1). For reasons already well studied (Giménez, 2003 and Olcina-Cantos, 2004), since the 1960s, this area has become one of the main tourist destinations in the world, with one of the highest rates of population and construction growth in Europe - unfortunately, to a large extent, in an uncontrolled way (Vera-Rebollo, 2005). This uncontrolled process of land occupation led to a series of environmental tolls, including an increase in the number of floods. Regardless of the materialization or not of the projected trends of climate change, the waterproofing and sealing of the soil in the Mediterranean area, experienced during all those years (Añó Vidal *et al.,* 2005; Valera Lozano *et al.,* 2011; Pérez Morales *et al.,* 2016), played a determining role in this exponential increase in flood events. The answer to such problems has been forged over time in such a way that, today; the technology-based solution continues to prevail over adaptation and prevention.

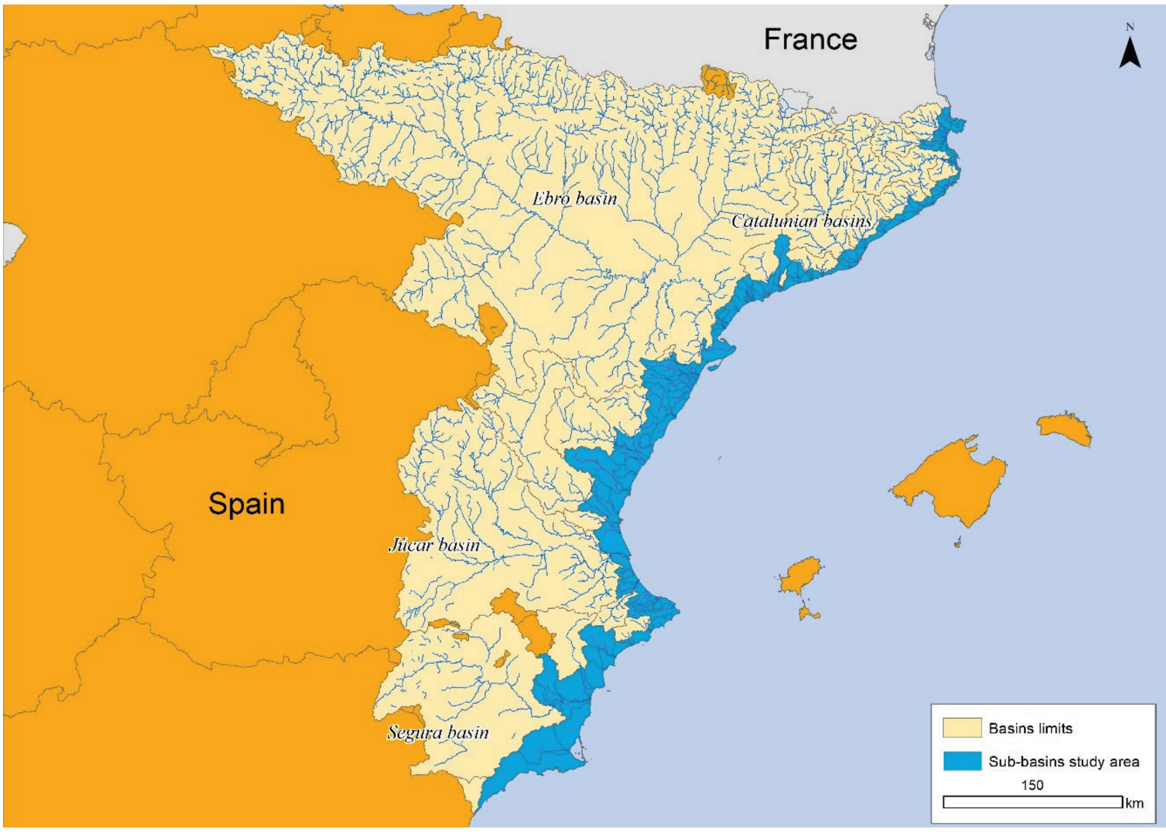

Figure 1. Location of the study area (Source: own elaboration).

The afore mentioned sequence that led to the current state of taking structural measures to control floods began with the process of modernization of the country and the demographic growth experienced during the 20th century. The second phase of the demographic transition in Spain was followed by the consequent occupation of new spaces, mostly for agricultural use, which inexorably caused an increase in both the demand for water resources and the territories affected by the risk of flooding. To tackle both issues, and taking into account the technological advances achieved up to that timeas well as the 19th-century experiences of the first large dams in the rivers of the Peninsula (Gil Olcina, 1992, 2002), strategies based on structural measures were implemented to mitigate the violent flood waves that flowed through the riverbeds and, at the same time, to retain flows for use as drinking water or irrigation, mainly during periods of low water supply. The result was a firm commitment at the state level to these defensive infrastructures and at the beginning of the 20th century the "Progress of a General Plan for Swamps and Irrigation Canals" was published, aimed at solving the irregularity of the river regimes through the construction of reservoirs with sufficient dimensions. According to this document, practically all these types of works had to assume the double purpose of laminating flood and regulating flows, allowing the establishment of reserves.

The technological approach was consolidated in the times of Primo Rivera and with the failed projects of the Second Republic (Pérez-Morales, 2009). In those years, the regenerationist ideas that penetrated the heart of Spanish society in response to the crisis of the late 19th century found their maximum expression in the creation of the hydrographic confederations. The principle of the use and integral defense of the basin of a main river was then accepted. These two concepts became irretrievably inseparable from the moment that a commitment was made to the construction of reservoirs as hydraulic works for the control and regulation of the flows circulating through Spanish rivers.

Since then, the number of structural measures has continued to grow, the maximum defense capacity being reached at the end of the 1970s with regard to dams (Córdova, 2008). Unfortunately, registries such as the Consorcio de Compensación de Seguros (CCS, 2018) and data bases such as: Carmona and Ruíz (2000) in Comunitat Valenciana; Romero-Díaz and Maurandi-Guirado (2000), Castejón-Porcel and Romero-Díaz (2014) in Region of Murcia, Llasat and Barriendos (2005) in Cataluña, and Gil-Guirado and López-Martínez (2019) in the Mediterranean Spanish coast, show that the problem, far from being solved, has worsened over time as the exposure to flooding has increased. In recent years it has become clear that, despite having a costly system of regulation and defense (without completely underestimating its effectiveness), every time a flood occurs, confederations and regional and local administrations are forced to respond through infraestructures (channeling and storm tanks) that have the sole purpose of amending the situation by patching-up the defensive system until another episode takes place.

3. Sources and methodology

To achieve the objectives of this work, a two-step sequential procedure was carried out. First, the database of the structural measures of the study area was configured. For the cataloging, localization, and dating of these actions, a search was made for three types of infrastructure that have been built and are in operation: dams, channeling, and storm tanks. The variables that make up the database are:

- Id: the identification number of each of the structural measures.
- Type of action: the following infrastructures were selected for the study: dams, channeling, and storm tanks.
- Name of the action: the official name of each of the infrastructures.
- Coordinates (x, y) in ETRS89 format, for georeferencing the structural measures.
- Year of construction: the year of completion of each of the works was taken as a reference.

- Status: the current situation of the infrastructure, whether or not it is in use or under construction.
- Municipality: the municipality in which the action is located.
- Channel: the channel on which the infrastructure has been built, or the channel that feeds it with its waters.
- Basin: the hydrographic basin to which it belongs.
- Capacity: the maximum storage capacity allowed by the infrastructure (in the case of dams and storm tanks).

The consultation procedure followed to compile all this information used primary and secondary sources (see Table 1). Regarding the former, a temporal analysis of aerial orthophotos from different flights over the study area (1956, 1981, 2002, 2016) was carried out. Through photointerpretation, different easily perceptible actions such as channels or dams were compiled. Once those identified through secondary sources had been discounted, the year of construction was revealed by specifically consulting digital files, press releases, or contrasting aerial orthophotos from different years, with the intention of determining as accurately as possible when they were carried out. The viewers used for the photointerpretation were: The Territorial Information System (https://sitmurcia.carm.es/); National Plan for Aerial Orthophotography (PNOA) (https://pnoa.ign.es/); Valencian Spatial Dades Infrastructure (http://idev.gva.es); Fototeca (https://fototeca.cnig.es/); Instituto Geológico y Cartográfico de Cataluña (https://www.icgc.cat/es/); and Instituto Cartográfico Valenciano (http://www.icv.gva.es/va/). The results obtained with this methodology made it possible to identify, and date the years of construction of 25 structural measures that did not appear in the secondary sources.

Regarding the search carried out in secondary sources, the following were consulted:

- National System for Flooding Zones Cartography (SNCZI in Spanish) of MAGRAMA (Ministry of Agriculture, Food and Environment). This tool, developed as part of the application of the European Directive 2007/60 on the evaluation and management of floods, incorporates the inventory of dams and reservoirs in Spain. In it, one can consult the geographical location, data on the basin, reservoir capacities, status of the security documents, technical data, photographs, and plans of the dams.
- Database of the Society of Dams and Reservoirs (SEPREM). This institution has a web service that provides information on these infrastructures, such as the year of construction and the capacity.
- Inventory of Spanish Dams. Spanish National Committee for Large Dams (SPANCOLD).
- Official information from Hydrographic Confederations, obtained by exhaustive searches in their geographic information viewers. The geographic information viewer of the Segura Hydrographic Confederation (CHS in Spanish) offers great possibilities when it comes to obtaining information, since it has a spatial database dedicated to infrastructures. In it, one can find data on dams and reservoirs, as well as on more specialized infrastructure when looking for more measures. The Júcar Hydrographic Confederation (CHJ in Spanish) offers practically the same service as the CHS; however, it should be noted that, on its website, the CHJ has information on the actions carried out in the Júcar basin, such as the technical files on the infrastructures built. This provided data on the location and specific details of each of them for the present work. Likewise, for this same demarcation, information was compiled on the actions planned as of 2003 according to the Territorial Action Plan of a sectoral nature on the Prevention of Flood Risk in the Valencian Community (PATRICOVA) (GV, 2003). The Ebro Hydrographic Confederation (CHE in Spanish) also has a cartographic viewer that provides

information on dams and reservoirs, in addition to some actions carried out, although not of a structural nature. The present study focused on the eastern part of the Ebro basin in the area closest to the Mediterranean Sea: the province of Lleida and the delta in the south of Tarragona. Regarding Catalonia, the consultation of the Catalan flood plan (INUNCAT) (GC, 2010) was also useful, since it offers data on infrastructure projects for defense against floods. The Catalan Water Agency (ACA in Catalan) was also consulted, yielding a list of numerous channelings for which it was necessary to complete the work with photointerpretation and geolocation.

- The last of the secondary sources was a bibliographic review of research articles and books, to complete the information on an action or find evidence of works not previously identified. Some of the most important publications are: Segura basin, Grindlay and Hernández, 2007, Pérez-Morales, 2008; in Júcar basin, Marco, 2012.

Table 1. Summary table of consulted sources (Source: Own elaboration).

Name	Source	Primary/secondary	Year
Orthophotos	– The Territorial Information System (https://sitmurcia.carm.es/); – National Plan for Aerial Orthophotography (PNOA) (https://pnoa.ign.es/); – Valencian Spatial Dades Infrastructure (http://idev.gva.es); – Fototeca (https://fototeca.cnig.es/); – Instituto Geológico y Cartográfico de Cataluña (https://www.icgc.cat/es/); – Instituto Cartográfico Valenciano (http://www.icv.gva.es/va/)	Primary	1956-1957; 1973-1986; 1980-1986; 1997-2003; 2004-2019
National System for Flooding Zones Cartography (SNCZI)	MAGRAMA (Ministry of Agriculture, Food and Environment)	Secondary	2015
Database of the Society of Dams and Reservoirs.	Society of Dams and Reservoirs (SEPREM)	Secondary	2020
Geographic information viewers	– Segura Hydrographic Confederation (CHS in Spanish); – Júcar Hydrographic Confederation (CHJ in Spanish)	Secondary	2020
Territorial Action Plan of a sectoral nature on the Prevention of Flood Risk in the Valencian Community (PATRICOVA)	Generalitat Valenciana	Secondary	2003
Catalan flood plan (INUNCAT)	Generalitat de Catalunya	Secondary	2010
Inventory of Spanish Dams. Spanish National Committee for Large Dams	Comité Nacional Español de Grandes Presas. SPANCOLD	Secondary	1970, 1973, 1986, 1991, 2006
Bibliographic review of research articles and books	Grindlay and Hernández, 2007, Pérez-Morales, 2008; Dios, 2008; Marco, 2012.	Secondary	2007, 2008, 2012

The second step of the methodology combined through spatial analysis with a GIS the database of structural measures with the parcels of the cadastre (MHAP, 2020) and the flooded areas of each of the SNCZI return periods, both in vector format. For this, the procedure proposed by Pérez-Morales *et al.* (2015) was used. Firstly, the cadastral parcels were associated with the hydrographic sub-basins of the study area in which they are found, through the spatial joint geoprocess. Subsequently, the cadastral parcels likely to be affected in the flooded areas of each of the return periods were identified through a selection of parcels based on their location in the flooded areas. Once this spatial database had been prepared, the years of construction of the cadastral parcels and the dams were listed. In this way, the year from which the sub-basins of the study area began to be regulated was identified and the percentage increases in cadastral parcels registered from the year following the start-up of each dam could be evaluated. Finally, a database was obtained that allowed us to evaluate the urban growth experienced in basins with and without a dam and to test the starting hypothesis.

4. Results

Figure 2 represents the 300 structural carried out in the period 1594-2016 and which are still in operation. From its analysis, several issues emerge. First, there are two well differentiated stages that confirm what has already been pointed out by Smith and Petley (2009). In the first, it was attempted to control the water resources for the human supply, irrigation, and hydroelectric production by means of large public works in the form of dams (Fig. 2a). In the second, since the end of the 1980s, where an accentuation can be seen, unprecedented defensive actions due to the increase in catastrophic flood events were performed (Quevedo, 1963; Mateu, 1990; Berga, 1997, 2003; Olcina-Cantos and Rico Amorós, 1999; Pérez-Morales, 2010) motivated by unorganized processes of transformation and occupation of the territory that were experienced in previous decades (Olcina-Cantos *et al.*, 2016) (Fig. 2b). For all the Spanish hydrographic basins, these actions had administrative and legal support when the Regulation of the Public Administration of Water and Hydrological Planning was approved (BOE, 1988). In these state regulations, reduction of the vulnerability to flooding was considered one of the main objectives (Olcina-Cantos, 2007).

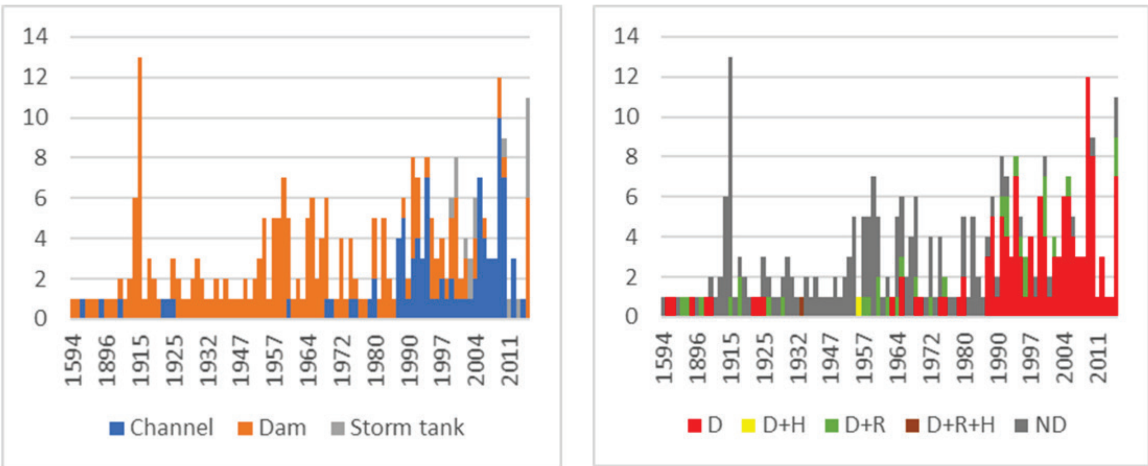

Figure 2. Evolution of the number of structural measures in the study area by type (a) and by use dedicated to defense and other purposes (b). Legend: D: Defense; D+H: Defense and Hydroelectric; D+R: Defense, Resource, and Hydroelectric; Not dedicated to defense (Source: Database).

In Figure 3 we can see a spatial distribution of the structural measures carried out in the study area. A higher density is observed in the rivermouth areas than upstream. As has already been pointed out, most of these coastal nuclei have undergone very rapid growth over the last few years that has motivated the creation of an important network of channeling to be able to safely integrate the hydrographic network into the urban area. A similar process has happened with the creation of storm tanks, which, being more recent devices, did not begin to be used as a solution until the end of the 20th century.

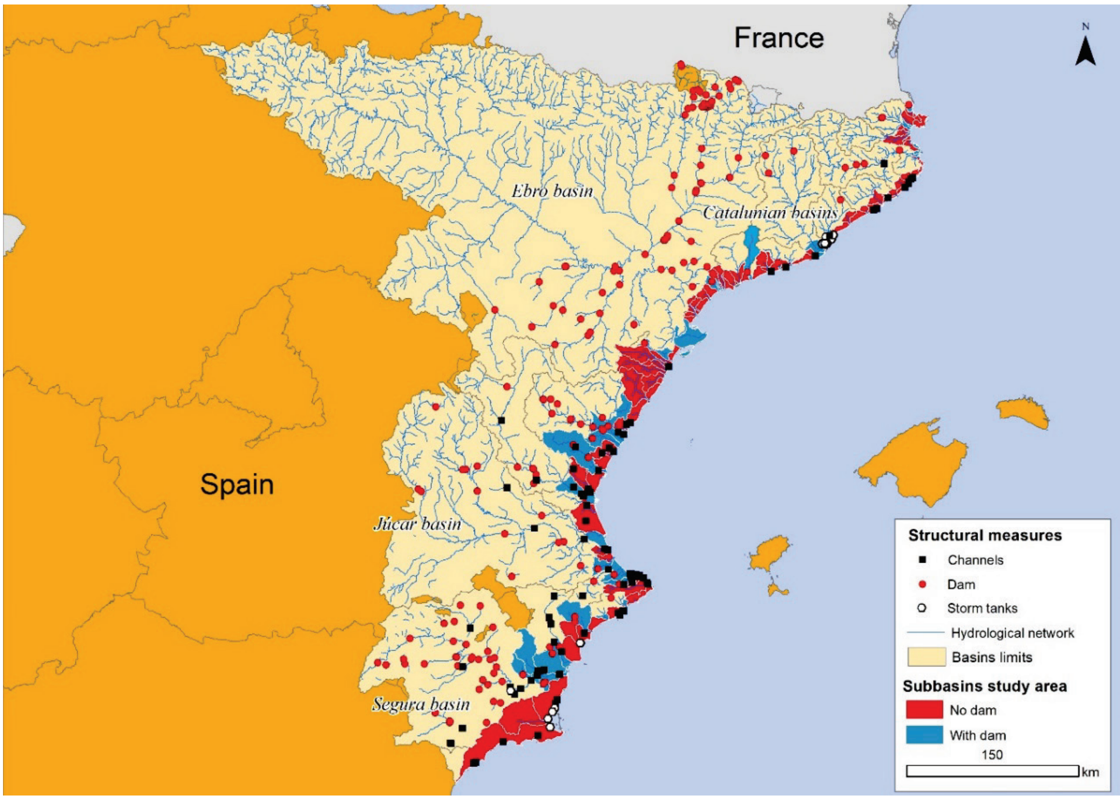

Figure 3. Distribution map of the structural measures (Source: Database).

4.1. Dams and reservoirs

The fluvial regime associated with the dynamics of the Mediterranean climate leads to long periods of low waterflow, suddenly interrupted by large flood events. Despite these dynamics being completely natural, demographic pressures and activities derived from this growing population urgently demand this type of expensive infrastructure in order to solve the risks of drought and flooding. The evolution since the construction of the first dam in Spain (1594, Tibi, Alicante) has been subject to periods of both firm support for these infraestructures and complete hostility (Gil Olcina, 2002; Pérez-Morales, 2009). On the purpose and constructive trend of dams in Spain, the bibliography (Córdova, 2008) indicates that they have gone from seeking only the regulation of channels through reservoir construction to overcoming periods of drought and having permanent water resources with which to irrigate, to a final stage in which the viability of reservoirs for irrigation is questioned and reservoir and hydroelectric production remain as the only justification for their construction. The afore mentioned can be seen in Figure 4.

However, although the trend seems stable, several factors could change it: the increasingly complicated task of finding suitable places to build dams, the Water Framework Directive, which is committed to quality rather than quantity, the commitment to desalination after the repeal of the National Hydrological Plan, environmental pressure, and the economic crisis of 2008 that drained resources for public works have been a perfect storm for these projects.

From a spatial point of view (Fig. 5), it should be noted that some of the flood-control reservoirs are located far from the coast because their construction directly conditions the downstream regions that are in the same basin. An example of this are the structural measures carried out in Castilla-La Mancha and Aragon. The effectiveness of flood control dams declines as their distance from the population centers to be protected increases. There are two reasons for this: the possibility of flooding in unregulated areas and the loss of lamination as the distance downstream increases (Ayala, 2002).

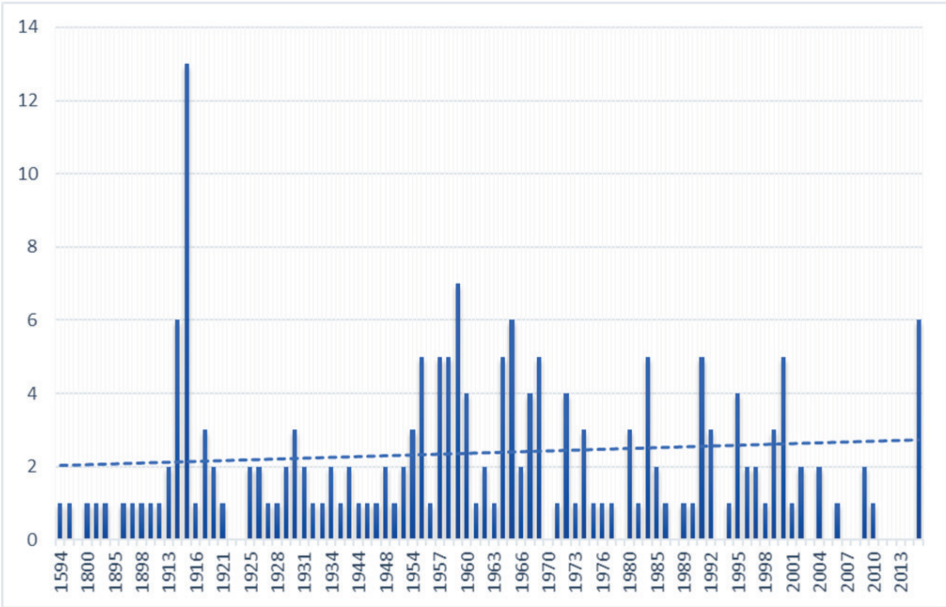

Figure 4. Evolution of dams and reservoirs (1594-2016) (Source: Own elaboration).

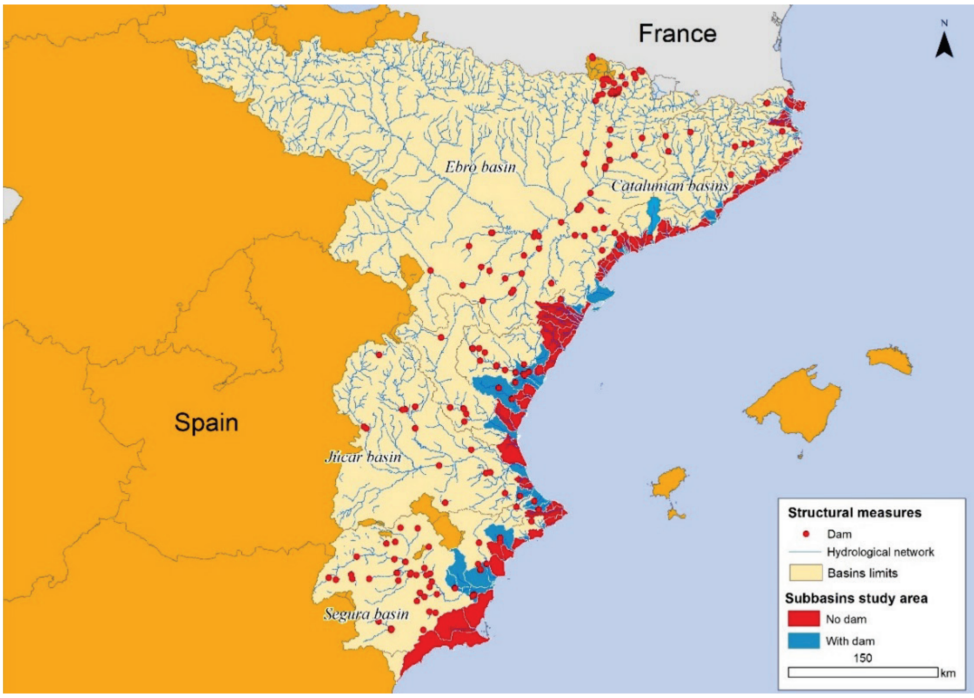

Figure 5. Map of the distribution of dams that affect the sub-basins of the study area. (Source: Own elaboration).

4.2. Channeling

Channeling has shown constant growth up to the present time (Fig. 6). As has already been pointed out, since the 1990s this type of artificial channel modification has been the preferred action of regional and local administrations to improve the drainage and defense of flood prone areas that have been progressively occupied in coastal municipalities. It could be said that administrations have found, in this type of work, the fastest and cheapest way to respond to the problems posed by the progressive ocupation of riverbeds due to their lack of management.

In relation to this trend, a part of society has called loudly for the establishment of a new relationship between rivers and the population through the replacement of traditional infrastructures by others that respect the fluvial environment. This implies that flood prevention should be compatible with the construction of infrastructures that favor the return of channels to their most natural state possible. However, although this movement is trying to impose itself in today's society, seeking a change in the management of hydraulic policy and the risk of flooding, the data collected show that conventional hydraulic infrastructures continue to be the option that is mostly chosen in areas where, until now, little has been done in terms of controlling the forces that increase vulnerability; fundamentally, urban growth (Roset-Pàges *et al.,* 1999) (Fig. 7).

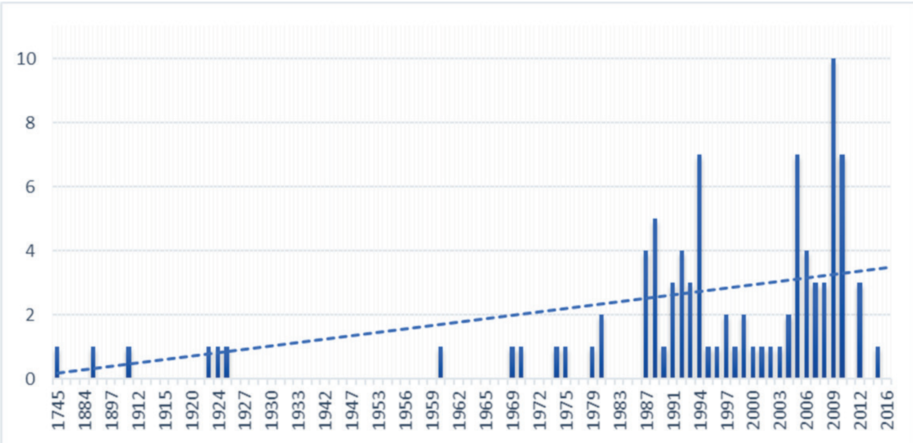

Figure 6. Evolution of channeling (1745-2016) (Source: Own elaboration).

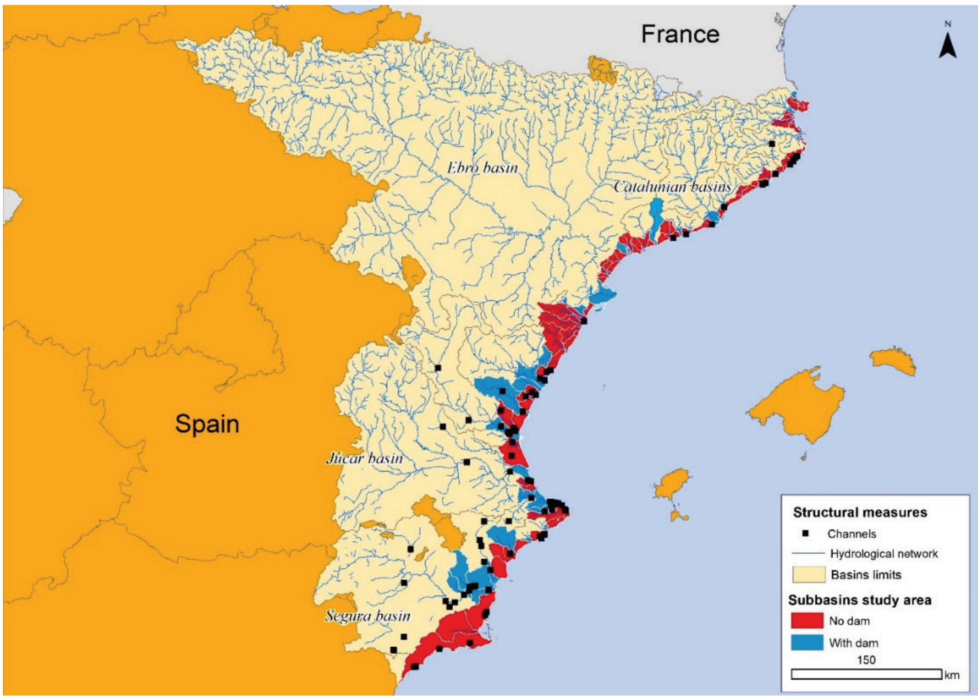

Figure 7. Channeling distribution map (Source: Own elaboration).

4.3. Storm tanks

Storm tanks, also known as spillways, are sewerage infrastructures consisting of a tank dedicated to capturing and retaining the rainwater transported to it by the collectors, especially when there is very intense rainfall, to reduce the possibility of flooding in the cases in which the drainage capacity of the water is less than the volume of rain. These tanks also have a pre-purification function by preventing the first rainwater - the most polluted because, although the rain is very clean, it produces a washing of the asphalt- from being dumped directly into natural aquatic systems such as rivers. Instead, wastewater treatment is carried out so that, once it is decontaminated, the water can be discharged into streams or bodies of water for later use.

These devices designed to laminate the maximum flows of an avenue are particularly important in areas where there has been massive waterproofing of the basins (Lessard and Beck, 1991; Andrés-Doménech *et al*., 2012; Ayesa, 2016). A good example of the above can be found on the East coast of the Autonomous Community of the Region of Murcia. In the immediate populations, this device was chosen with the dual objectives of reducing floods effects and decanting pollutants in the form of fertilizers and pesticides generated by intensive agriculture and that are responsible for the ecological disaster of the Mar Menor (Perni and Martínez-Paz, 2013; Pérez-Morales *et al*., 2016).

As can be seen in Figure 8, the first storm tank in the study area was built in 1999 (Gago, 2010); therefore, it can be considered as a recent solution. Since then, the proliferation has been constant and these actions have been gaining importance, in both number and dimensions, within what are known as sustainable urban drainage systems (SUDS) (Castro *et al.,* 2005).

The location map (Fig. 9) shows how these infrastructures are located at river mouths, mostly on the coast. In Barcelona there are nine, distributed throughout the city, that try to solve the drainage problems of the city. The province of Alicante has two storm tanks; the first was inaugurated in 2011 and has a capacity equal to that of 24 Olympic swimming pools (Hernández and Morote, 2019). In the Region of Murcia, four storm tanks of the twenty-one projected for the Mar Menor have been built in the last two years, as part of the project "Vertido Cero" (García *et al.,* 2017).

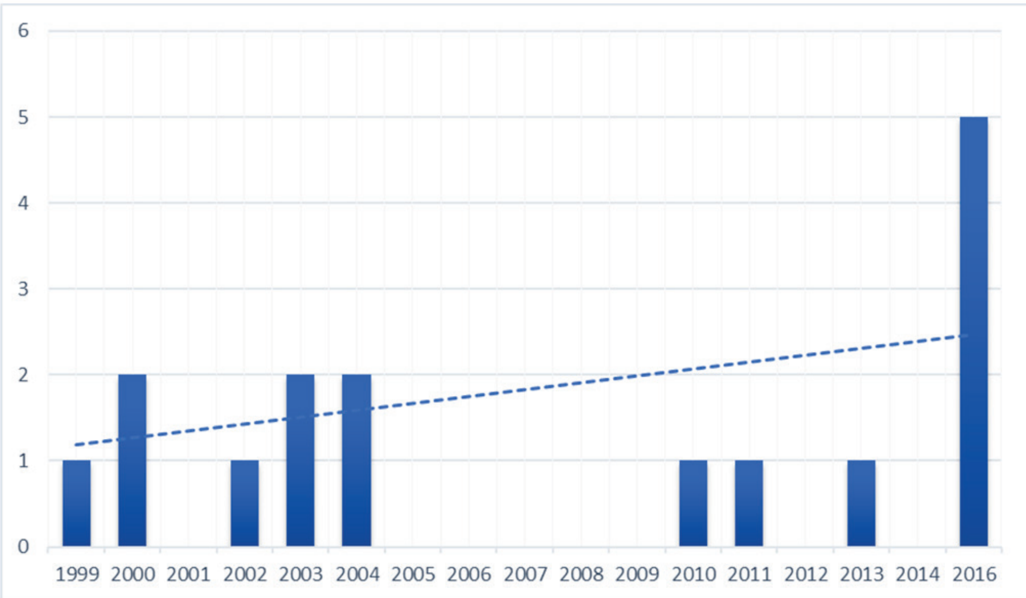

Figure 8. Evolution of the construction of storm tanks (Source: Own elaboration).

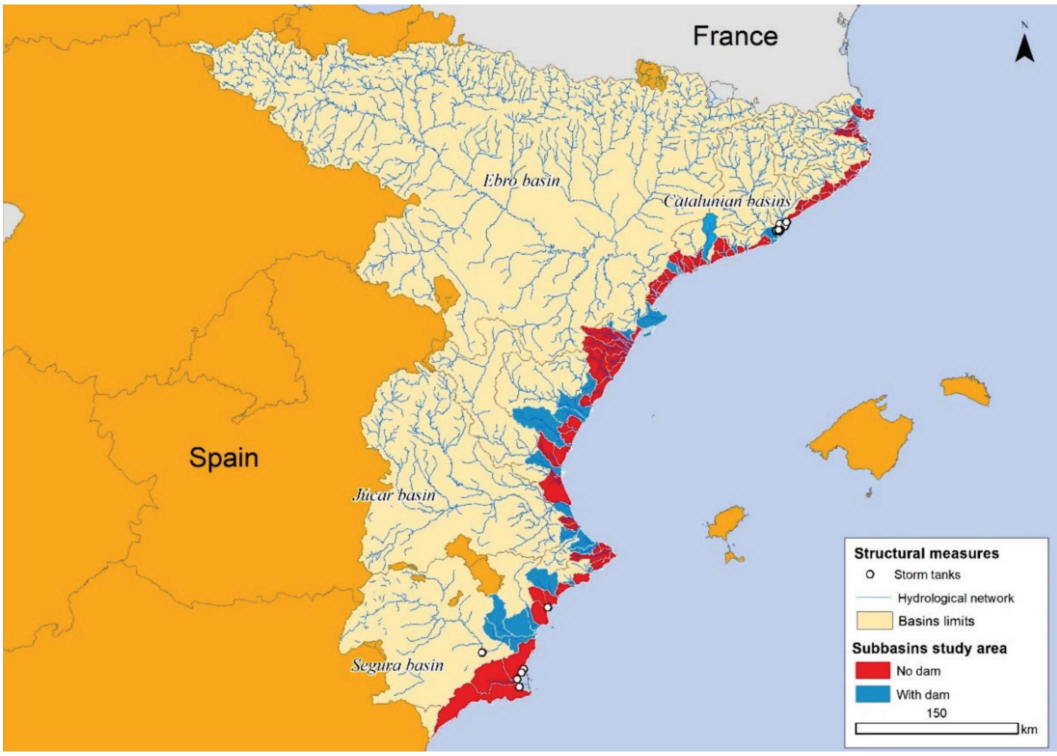

Figure 9. Storm tanks distribution map (Source: Own elaboration).

4.4 Evidence for the persistence of the "escalator effect" in the study area

The socioeconomic changes experienced in the last four decades in Spain have had a special impact on the land and, therefore, on its exposure to natural hazards (Barredo *et al.,* 2012). This process has been especially intense and marked in the littoral area, where recent urban growth linked to urban-tourist development has been described as a true "urbanizing tsunami" (Gaja, 2008). According to the results of Figure 10, since 1975 the urbanized area and the number of buildings that occupy each of the flood zones for the return periods studied (10, 50, 100, and 500 years) have undergone a continuous accumulated growth on the coast of the provinces of Murcia and Alicante.

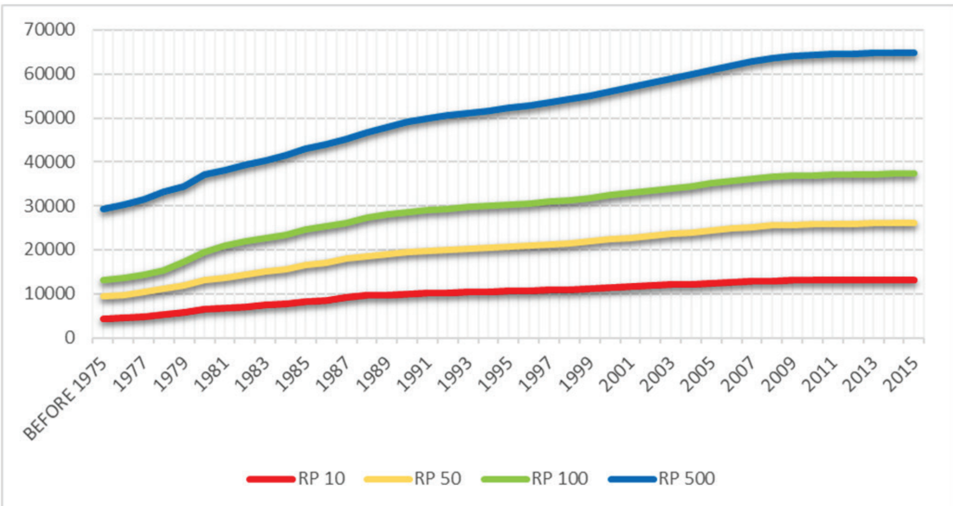

Figure 10. Evolution of the number of buildings built in each of the return periods areas (1975-2016) (Source: Own elaboration).

In relative terms, the results are truly alarming. For the period analyzed, the increase in urban parcels was 347% (<1975 = 100), which represents an annual growth rate of 8.9%. However, it is striking that the growth of urban parcels in areas prone to flooding has been greater than in safe areas (273%).

As can be deduced from the previous data, the regulation of floodplains in the study area has been conspicuous by its absence or its limited effectiveness (López *et al.,* 2020 and Ribas *et al.,* 2020). According to the works consulted in this regard, in recent decades floodplain management policy have not stopped the occupation of flood prone areas in the study area (Pérez-Morales *et al.,* 2015) except in those areas where the delimitation of the Domain Public Hydraulic was made (Olcina-Cantos, 2007) or by the presence of a continuous flow. According with the last, in the present work we wish to determine if this practically incessant trend has been homogeneous across all the basins of the study area or, on the contrary, there are differences between those regulated by dams and those that are not, due to the "escalator effect".

The results obtained partially validate this hypothesis (Table 2). There is a statistically significant difference (p-value < 0.05) in the proportion of buildings built in the most probable flood zone of the four analyzed, that of RP10, between the sub-basins with and without a dam. In the rest (RP50, RP100, and RP500), the percentage of buildings erected in floodplain areas in unregulated basins with dams is higher than in those without a dam (p-value >0.05). In other words, there is a progressive occupation of potentially floodable areas in the zones closest to the riverbed.

Table 2. Inferential statistics of real estate activity in basins with and without a dam in the study area (Source: Own elaboration).

Return period	No. cadastral parcels built in flood prone areas in a subbasin with a dam	% (100=Cadastral parcels in areas not prone to flooding)	No. cadastral parcels built in flood prone areas in a subbasinwithout a dam	% (100=Cadastral parcels in areas not prone to flooding)	p-value (0.05)
RP10	18199	4.4	4905	3.7	0.032*
RP50	26556	6.4	6756	5.4	0.138
RP100	42316	10.2	14678	11.3	0.509
RP500	49099	11.9	19935	15.4	0.900

To reinforce the above evidence, the percentage increases in the buildings built in basins regulated and not regulated by dams -from 1975 to the present - were compared, regardless of whether or not they were built in a flood zone. The year 1975 was taken for two fundamental reasons: regardless of the year of construction of the dam, the precision of the data from the cadastral source is greater thereafter (García Martín, 2013) and, above all, because it marks the start of the major processes of occupation of the coastline in Spain (Pérez-Morales *et al.,* 2015). According to the data commented on above, the contrast between the percentage increase in what was built between basins with a dam and those without a dam does not allow us to confirm the hypothesis (p-value <0.05). However, a higher mean growth (140.3% without a dam versus 156.1%) and median (104.6% without a dam versus and 145.6%with a dam) is observed in hydrographic basins where there is a reservoir to protect downstream areas (Fig. 11).

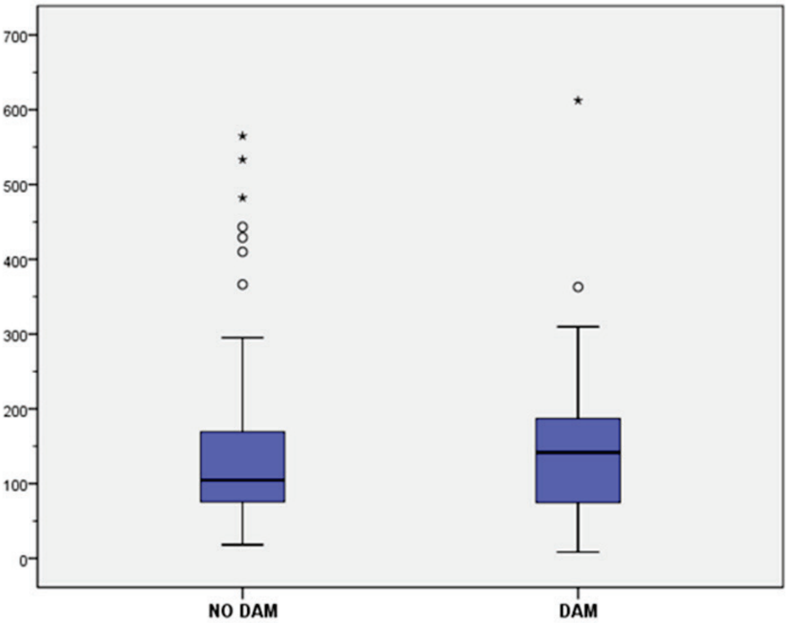

Figure 11. Boxplot showing percentage increase in cadastral plots in sub-basins with and without a dam (1975-2015) (Source: Own elaboration).

5. Conclusions

Structural measures have not stopped growing in number and size in the study area. Throughout the 20th century and up to the present, an ascending trend line can be seen. In that trend two phases of growth can be observed. In the first half of the century, the actions were mainly limited to dams and reservoirs capable of regulating channels, to supply a growing population with water resources and defend it from flood waves. In the second half of the century, this population increase, which had been making greater demands in terms of space and water for both agricultural and urban use, accelerated the progressive occupation of the riverbeds with the consequent increase in flood events and associated economic losses. At this point large supply projects ceased to be important due to, among other reasons, a lack of space for the location of profitable dams. Meanwhile, the necessary debate on the convenience between preventive and structural measures began, channeling gaining in importance as an immediate and more economical solution to solve the increased exposure to the increasingly frequent floods. More recently, storm tanks have complemented the work of such channeling. It is possible that the importance of storm tanks will be greater in the future due to the advantages that they offer, namely: defense against floods, purification of contaminated water, and its subsequent use as non-potable water.

A plausible explanation for this type of cognitive dissonance of the population when occupying floodplains, despite its negative consequences, seems to be given by the "escalator effect". The results obtained in the study area allow this hypothesis to be partially validated, since only in the floodplain area with the highest probability of occurrence of flooding (RP10) has urban growth (p-value <0.05) been greater in watersheds with a dam than in those without. To consolidate this confirmatory finding, the percentage increases from 1975 to the present in the urban growth in basins regulated and not regulated by dams were compared, regardless of whether or not they were built in a floodplain. The result is not clear in terms of statistical significance (p-value>0.05), but the percentage growth is higher in basins with a dam than in those without one. In this sense, our results are consistent with Collenteur *et al.* (2015).

The fact that the results in the study area are not entirely conclusive could be due to two main reasons: firstly, the natural characteristics of the channels analyzed and, secondly, the differences in behavior between urban typologies of the population centers. The riverbeds are mostly represented by ephemeral channels which, lacking a continuous flow and if not delimited, easily become ideal land for use in basins both with and without regulation. Quite a different situation exists when the flow is continuous and the space occupied by a river module is physically recognized. In these cases, the spatial differentiation between basins, in order to carry out the contrast, is simpler, as seems to be the case in the areas analyzed by Parker (1995). With regard to the populations of the study area, there are at least three types of urban nuclei with different construction trends: regional and provincial capitals, medium-sized cities, and populations of less than 50,000 inhabitants. This urban heterogeneity represents an added difficulty when establishing a generalization and a comparison of basins, since the construction trends of the populations tend to be very divergent from each other.

Acknowledgement

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WHAT CAN WE LEARN FROM THE PAST? A CENTURY OF CHANGES IN VULNERABILITY TO FLOODS IN THE TER RIVER BASIN

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ABSTRACT. The objective of this article is to analyze from a historical perspective the impacts of floods in the Ter river basin of North-Eastern Catalonia between 1900 and 2020. The analysis focuses on the three factors that, according to the IPCC, intervene in the definition of vulnerability, namely exposure, susceptibility and adaptive capacity. The analysis has been structured in four historical periods with two or three catastrophic flood episodes for each period. Although a lack of reliable data and studies on especially economic losses must be acknowledged, results obtained indicate that flood exposure has increased in the basin but vulnerability may have decreased as a result of decreased susceptibility and, especially, of a significant increase in adaptive capacity. Both in terms of victims and relative economic losses, the impacts of the floods would show a downward trend that, among other factors, tends to correlate positively with the increasing levels of economic development and well-being experienced in the basin during the last century.

¿Qué podemos aprender del pasado? Un siglo de cambios en la vulnerabilidad a las inundaciones en la cuenca del río Ter

RESUMEN. Este artículo tiene por objetivo analizar, desde una perspectiva histórica, cuáles han sido los impactos de las inundaciones en la cuenca del río Ter durante el período comprendido entre los años 1900 y 2020. El análisis se centra en los tres factores que, según la aproximación a la vulnerabilidad que propone el IPCC, intervienen en el impacto de las inundaciones: exposición, susceptibilidad y capacidad de adaptación. Metodológicamente, este análisis se ha estructurado a partir de la selección de cuatro períodos históricos y dos o tres episodios de inundación catastróficos para cada período. Aunque faltan datos y estudios concluyentes especialmente sobre pérdidas económicas, los resultados obtenidos indican que, si bien la exposición a las inundaciones ha aumentado y los daños han seguido una tendencia ascendente, la vulnerabilidad ha disminuido a consecuencia de la disminución en la susceptibilidad y, especialmente, a un importante aumento de la capacidad de adaptación. Tanto en términos de víctimas como de pérdidas económicas relativas, los impactos de las inundaciones mostrarían una tendencia a la baja que, entre otros factores, tiende a correlacionarse positivamente con los niveles crecientes de desarrollo económico y bienestar que ha experimentado esta cuenca.

Key words: Historical floods, vulnerability, exposure, susceptibility, adaptive capacity, Ter river basin.

Palabras clave: Inundaciones históricas, vulnerabilidad, exposición, susceptibilidad, capacidad de adaptación, cuenca del Ter.

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1. Introduction

Throughout human history, floods have been and remain the most important natural hazard worldwide regarding people affected (Kron, 2015; Angelakis *et al.*, 2020). Between 1980 and 2019, flooding accounted for some 40 percent of worldwide natural disaster losses, totaling more than 1,092 billion US dollars (Munich Re, 2019). Moreover, flood occurrence appears to be increasing. For example, the number of major world floods per year rose from an annual average of 127 for the period 1995-2004 to an average of 171 in the period 2005-2014 (Munich Re, 2019). In Europe, between 1980 and 2010, 37 European countries recorded more than 3,500 flood episodes (EEA, 2016) but possible many more did not reach official statistics (Paprotny *et al.*, 2018).

Climate change exerts an increasing influence in future flood trends. In Europe, for instance, floods associated with return periods of 100 years may double their frequency around 2050 (Alfieri *et al.*, 2015). Ensuing impacts are estimated to be very high with absolute economic damages increasing twenty-fold by the end of this century, especially in Asia (Winsemius *et al.*, 2016). In Europe, flood losses would increase five-fold by 2050 and 17-fold by 2080 (EEA, 2016). Most studies attribute the bulk of these growing impacts to socioeconomic factors rather than to natural factors. Hence, observed and expected losses are primarily related to an increase in exposure, basically the accumulation of population and wealth in flood prone areas which multiplies the potential of losses (Barredo, 2009; Rosenzweig *et al.*, 2018; UNISDR and CRED, 2019). In Europe, Paprotny *et al.* (2018) document increases both in annual flooded areas and in number of people affected since 1870.

However, increasing exposure does not necessarily translate into increasing negative impacts, at least in terms of human mortality. On the contrary, several studies have found declining trends in flood related mortality. In Europe, decline has been consistent at least since 1950 (Mudelsee *et al.*, 2003; Jongman *et al.*, 2015; Tanoue *et al.*, 2016; Paprotny *et al.*, 2018). Regarding economic losses, the picture may be more complex. In general, it can be argued that economic losses increase in absolute terms, but when “normalized” (e.g. considered in the context of the evolution of population, GDP and GDP per capita) may remain stable or even decrease (Barredo, 2009). Neumayer and Barthel (2011), for instance, did not find significant upward trends in normalized disaster losses for the period 1980-2009. Likewise, in a study of insured flood losses in Spain between 1971 and 2008, Barredo *et al.* (2012) did not observe an increasing pattern either.

Despite problems of under-reported smaller episodes and the always difficult monetary evaluation of all economic and non-economic losses, the impacts of floods using the metrics of victims and of economic damages appear to be historically declining a least in Europe and possibly in the world as well. For some authors, there is a clear relationship between the impacts of natural disasters and the level of development (Burton *et al.*, 1978). Rising standards of living between 1980 and 2010 coincided with falling mortality and falling economic losses normalized according to population and GDP (Jongman *et al.*, 2015). In this sense losses and wealth are intrinsically related (Schumacher and Strobi, 2011).

The findings summarized above concur with the hypothesis that exposure alone cannot give a meaningful assessment of flood impacts. Hence, impacts respond to changes in exposure to flood events but also and perhaps more importantly to changes in susceptibility such as the characteristics of the population and the socioeconomic activities potentially exposed to the hazard and to changes in adaptive capacity or ability to respond adequately to extreme events. Vulnerability would finally result from the dynamic interplay between these three components: exposure, susceptibility and adaptive capacity, according to the approach to vulnerability taken by the IPCC (IPCC, 2014, Schmidt-Thomé and

Grieving, 2013) that will be followed in this article. Historical changes in the three components of vulnerability would provide a reasonable explanation for the temporal evolution of flood related impacts and its human, social and economic significance. All three components have underlying causes that need to be unraveled (Blaikie *et al.*, 2005). Exposure is primarily related to flood events and its characteristics in terms of magnitude, frequency and spatial and temporal reach (Burton *et al.*, 1978). Susceptibility calls for attention to age, physical condition, class, gender, race and ethnicity, education and income, among other social variables, of the people and communities in the basin. Adaptive capacity is related to wealth but also to the quality of democracy, governance and rights (Ensor *et al.,* 2015). All components of vulnerability are deeply interwoven with historical and existing patterns of human occupation and use of the land, and with the socioeconomic model and related institutions, norms and values inspiring these patterns. According to Jongman *et al.* (2015), vulnerability remains an insufficiently explored variable and yet of high significance for projecting adequately future trends in flood victims and losses. Historical approaches to the occurrence and impact of floods may shed light therefore on changing views on the relations between extreme natural events and human societies.

Our objective in this paper is to offer a historical perspective on floods and their impacts in the Ter River basin (Northeastern Iberian Peninsula) by examining for approximately the last century exposure, susceptibility and adaptive capacity to these phenomena. More specifically, we will assess how several large floods since the early 20th century disrupted population, economic activities and infrastructures; what were in each period the responses to avoid or reduce future losses and what lessons could be learnt to reduce future vulnerability. By using a historical perspective, we can identify change, permanence and inertial factors for a given area regarding flood occurrence, responses and impacts as well as discourses and future strategies for flood control. Our main hypothesis, backed by recent research on long term impacts of natural hazards and of floods as summarized above, is that during the last century exposure to floods has increased and that damages have followed a consistently upward trend. However, overall vulnerability would have decreased owing to a decrease in certain dimensions of susceptibility and above all to an important increase in adaptive capacity (Jongman *et al.*, 2015). Both in terms of victims and of relative economic losses the impacts of floods would show a downward trend which, among other variables, tends to correlate positively with increasing levels of economic development and welfare (Burton *et al.*, 1978).

The paper is organized as follows. After this introduction, we present the study area and the materials and methods chosen for undertaking the analysis. Next, we begin our analysis of the changing conditions in the physical characteristics of catastrophic floods by selecting an analyzing four major historical periods in the Ter, and two or three major flood episodes for each period, ranging from 1900 to 2020. Each event is set in the dominant territorial model in the different sub basin areas of each period, and the characterization of exposure, susceptibility, and adaptive capacity are estimated for each territorial unit and period in order to estimate the respective vulnerabilities. Then, we discuss the results in the light of the main hypothesis formulated in the introduction and conclude with a summary of the paper and the main lesson learnt regarding the evolving character of vulnerability to floods in the study area.

2. Study area

With a length of 195 km and a basin area of 3,010 km^2, the Ter River is, together with Llobregat River, the most important fluvial course in Eastern Catalonia, flowing from the Pyrenees to the Mediterranean Sea (Fig. 1). Altitudinal differences from near 3,000 meters to sea level in less than 200 kilometers and a complex orography shape the large variety of climates and natural landscapes present in the basin. Mediterranean influences govern the pluvial and hydrological regime of much of the basin, with a maximum of rainfall in autumn and spring, dry summers with occasional rainfall outbursts, and winters with little rain. Central European influences accentuate the secondary winter drought, intensify spring and summer rainfall, and favor occasional but intense winter frosts. Highest precipitation, with average annual values above 1100 mm, occurs in the headwaters and decreases towards the coast where average values fall to 550 mm. Current average annual flow of the Ter River attains 816 hm^3 (26.6 m^3/s. at the mouth). The Ter River is regulated by two reservoirs, Sau and Susqueda, that, together with the secondary reservoir of El Pasteral, allow the transfer of up to 7.5 m^3/s and some 195 hm^3 every year to Barcelona. Additionally, 1,4 m^3/s are directed to the urban area of Girona and to the Center of the Costa Brava (18 hm^3 every year).

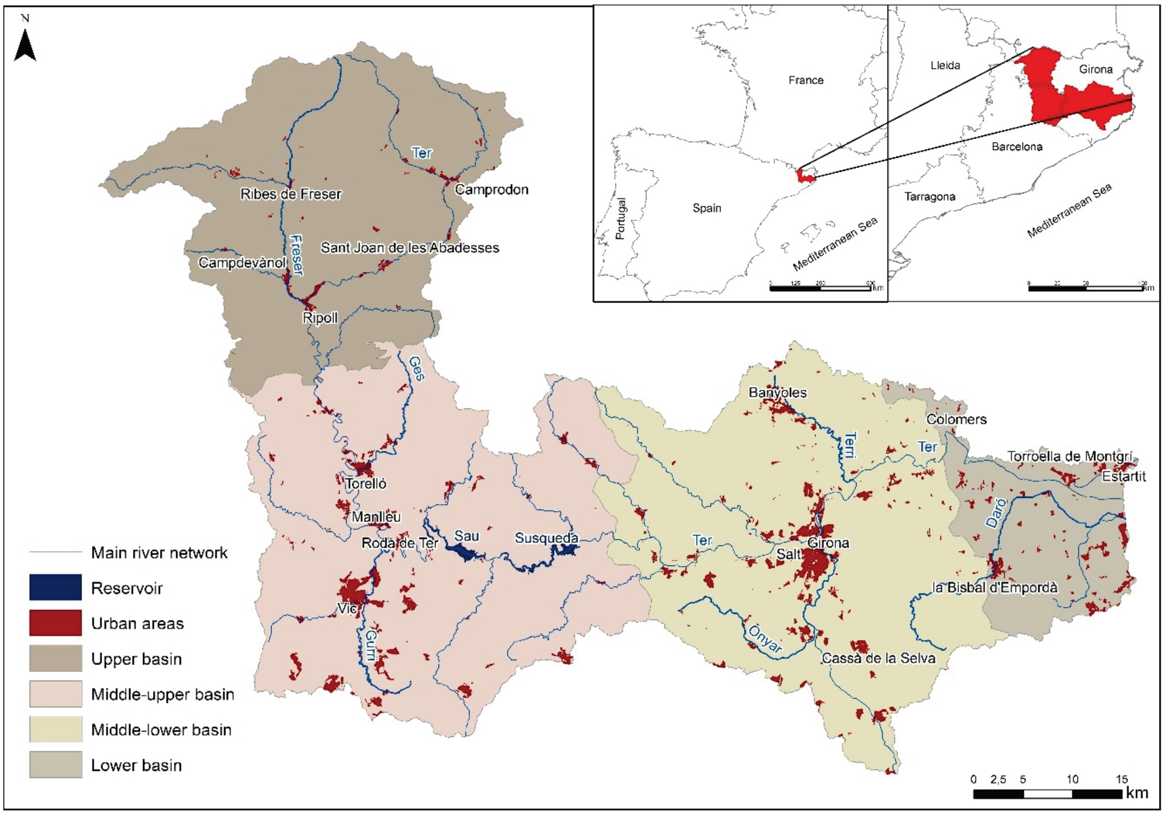

Figure 1. Ter River basin: Main river network, territorial models and urban areas.

From an environmental and socio-territorial point of view four major territorial units may be differentiated in the Ter basin:

1. The Pyrenean valleys of the Upper basin running through the Ripollés region. Historically, these valleys, of a complicated orography, have been sparsely settled with few major centers (Ripoll, Ribes de Freser or Camprodon) but poor communications. In recent years, the steady increase in mountain tourism (Vallter and Núria ski resorts, rural tourism and secondary dwellings) and the creation of protected natural areas (Parc Natural de les Capçaleres del Ter i el Freser) has contributed to a certain demographic and economic dynamism in an area that was severely affected by the crisis of traditional textile and metallurgic production since the middle of the 20^{th} century.

2. The Middle-upper basin comprising the Osona region bounded at its eastern end by the Sau, Susqueda and El Pasteral reservoir complex. Here, the Ter runs through the Plana de Vic, a passageway between the Pyrenees and the Catalan Precoastal mountain ranges. Textile mills, many of them profiting from the hydraulic energy of the Ter and tributaries made this part of the basin an important industrial enclave. Textiles today have lost their competitive edge to food processing industries based on livestock and especially on intensive pig farming. The towns of Manlleu, Torelló and Vic concentrate 90 percent of the population of this unit.

3. The Middle-lower basin encompassing part of the Selva and Gironés regions, and the southernmost part of Pla de l'Estany region. This is an area of gentle rolling hills and plains home to highly diversified economic activities, from agriculture and livestock to several industrial branches and the specialized services typical of the urban agglomerations. The most important population center in the entire basin, the city of Girona (101,852 inhabitants in 2019) specializes in the service economy (insurance, real estate, public administration, commercial sectors) as well as in urban tourism.
4. The Lower basin including the large alluvial plain of the Ter River and stretching from the southernmost part of the Gironés region and the northernmost part of the Baix Empordà region towards the sea. Irrigated agriculture (cereals, vegetables, rice and fruit trees), in the fertile lands of the interior, and mass tourism on the coast have shaped a very dynamic area, of which Torroella de Montgrí-l'Estartit is the main center. The Aiguamolls del Baix Empordà, located at the end of the Ter and the Daró rivers, today a natural park, has been the target of various policies for the preservation and restoration of wetlands (LIFE la Pletera, in the area of the Aiguamolls del Baix Ter) and promotion of natural and scenic values (Parc Natural del Montgrí, les illes Medes i el Baix Ter).

3. Methodology and data sources

The methodology used in this article is based on the collection and analysis of data and written texts related to episodes of extraordinary floods that occurred in the Ter River basin during the period 1900-2020. The analysis focuses on the three factors that intervene in the impact of floods: exposure, susceptibility and adaptive capacity, according to the framework proposed by the IPCC (2014). The choice of flood episodes is made according to Llasat *et al.,* (2005) who define catastrophic floods as "Precipitation episodes that cause the overflow of river courses and / or the accumulation of water on the surface and cause serious damage to people (victims) and / or property (bridges, buildings, crops, water infrastructure, buildings, factories, shops, etc.)". Following these criteria, we have selected for analysis 9 episodes in total, spread over 4 periods. This temporal division in four periods obeys to changes in the dominant models of territorial organization in the different subareas of the basin. The periods are as follows: 1) from the agroindustrial development of the early 20th century to just before the Spanish Civil War (1900-1935); 2) from the hardship of the war and postwar years to the completion of the Susqueda reservoir (1936-1969); 3) from the transformations brought about by tourism to the consolidation of democracy in Spain (1970-1985), and 4) the final period of intensification of population, urban and tourist growth (1985-2020) (Table 1).

Table 1. Catastrophic floods for different periods

Periods	Catastrophic floods
1900-1935	7-10 October 1919 15-19 December 1932
1936-1969	17-20 October 1940 11-12 October 1962 13 September 1963
1970-1985	11-12 October 1970 7 -8 November 1982
1986-2020	10-11 October 1994 19-23 January 2020

Own elaboration.

For the analysis of the magnitude of the selected flood episodes, we have used data of total recorded precipitation; average daily flow (Qc) and maximum registered or estimated flow (Qci). Precipitation data was provided by the Servei Meteorològic de Catalunya (SMC) and local observers. Hydrological data come from the Catalan Water Agency (ACA), the Hydrographic Confederation of the Eastern Pyrenees (CHPO) as well as various technical reports and scientific publications.

For the analysis of population growth in flood prone areas, we have used the population censuses of the municipalities that are part of the Ter basin and provided by the Institut d'Estadística de Catalunya (IDESCAT). The description of the main characteristics and impacts caused by each of the episodes derives from extensive content analysis of local and regional media sources, mainly *El Autonomista, Diario de Girona, El Punt Avui, El 9 Nou* and *La Vanguardia.* Memoranda and technical reports of damages caused for the most catastrophic episodes carried out by local, regional (Catalan) and national administrations containing detailed accounts of each episode, inventory of damages, planned reconstruction measures, etc. have been also a valuable source of information (for example, Comisaría General de Regiones Inundadas, 1942; Gobierno Civil de Gerona, 1964 y 1979; Llansó de Viñals, 1971). However, a note of caution should be introduced when presenting economic losses. Most data in this regard is quite heterogeneous and/or insufficient, especially for the oldest episodes. Moreover, studies of the evolution of losses using constant monetary units and studies of normalized economic losses (losses estimated in proportion to the economic wealth of each period) are lacking. Hence, appreciations are highly qualitative and based on aggregated data. We have also used scientific publications derived from research projects on the subject matter and specific plans, projects and maps included in river basin documents, emergency management proposals and the building of flood control infrastructure (Plan of Fluvial Areas of the Baix Ter, Special Plan for Flood Emergencies in Catalonia (INUNCAT), municipal emergency plans, etc.). From these documents two types of information have been obtained. First, data on precipitation, river flows and flood mapping which have helped in characterizing exposure to floods in the study area. Second, data on flood management actions currently existing in the basin have made possible an assessment of current adaptive capacity to this hazard.

4. Results

4.1. Physical characteristics of floods

The Ter basin has historically registered the largest number of floods in the fluvial basins of Eastern Catalonia, with 135 documented events for the period 1322–2020 (Llasat *et al.*, 2005; ACA, 2018 and updates by the authors). Floods in the Ter are mostly associated with episodes of precipitation of two basic types: First, episodes of short to medium duration (between 6 and 72 hours) with heavy rains lasting several hours and accumulating large amounts of precipitation (200–500 mm). These episodes occur mainly in autumn and sporadically in spring and may generate floods that affect the whole basin or a large part of it. Historically, this is the most important type of flood affecting the entire basin, although the construction of the Sau-Susqueda-el Pasteral reservoir complex in the middle of the 20th century has reduced flood flows downstream of these reservoirs. The second type are more localized episodes of very short duration (less than 6 hours) but of high intensity, such as the one that occurred in L'Estartit in October 1994. These episodes tend to appear during the summer and early autumn and produce mostly local flooding increasingly in coastal areas but can also occur in the upper part of the basin. The latest reports of the Spanish Meteorological Agency (AEMET, 2015), following the calculation parameters of the IPCC (2014), indicate that these local extreme precipitation events tend to be more pronounced and severe in recent decades. Moreover, they produce the so called “pluvial flooding” that is becoming the main type of flood in recent times (Ribas *et al.*, 2020).

Basic data and area affected by catastrophic floods in the Ter basin for the period 1900-2020 are shown in Table 2. These catastrophic episodes concentrated in autumn and usually involved a large part of the basin. Some extraordinary precipitation values (such as the 870.1 mm of Camprodon in the episode of October 1940) are of note. The hydrological response was generally fast since instantaneous maximum flows appeared either the same day or, at the latest, the next day. The most extraordinary peak flows in the Ter River occurred in the episode of October 1940 (2,350 m^3/s estimated in Roda de Ter and Girona and 2,400 m^3/s in Torroella de Montgrí).

Table 2. Catastrophic floods in the Ter River Basin (1900-2020). Precipitation and registered/estimated river flows for different meteorological and gauging stations

Episode	Area affected	Precipitation (mm)		River Flow (m^3/s)***		
		Meteorological station	P (mm)	Gauging station	Qc* (m^3/s)	Qci** (m^3/s)
7-10 October 1919	Basin	Ribes de Freser Sant Hilari Sacalm El Pasteral	347 334 305	Ripoll Roda de Ter Girona	240 578 n.d.	530 1,100 1,320
15-19 Decem.1932	Basin	Camprodon Ripoll Susqueda Girona Banyoles	586 332.7 519 428.8 519	Ripoll Roda de Ter Girona Torroella de Montgrí	418 863 n.d. 770	919 1,800 1,320 1,400
17-20 Octob. 1940	Basin	Camprodon Ribes de Freser Susqueda	870.1 375 437.1	Ripoll Roda de Ter Girona Torroella de Montgrí	450 1,237 n.d. 1,340	1,050 2,350 2,350 2,400
11-12 Octob. 1962	Middle-lower and Lower basin	Girona	190.2	Torroella de Montgrí	500	900
13 September 1963	Middle-lower and Lower basin	Girona	113.5	Ripoll Roda de Ter Torroella de Montgrí	223 770 740	634 1,300 1,340
11-12 Octob. 1970	Basin	Camprodon Ribes de Freser Vilallonga de Ter Girona Estartit	166 170 190 202 (24 hours) 137.6	Ripoll Roda de Ter Torroella de Montgrí Girona	275 400 620 597.5	1,050 1,066 1,100 971
7-8 Novemb. 1982	Upper basin	Ribes de Freser Susqueda	201 171 (24 hours)	Ripoll Roda de Ter	550 750	1,000 1,300
10-11 Octob. 1994	Lower basin	Torroella de Montgrí Estartit (Torroella de Montgrí) La Bisbal d'Empordà	381 320 (217.18 in 24 hours) 258.6	Estartit	n.d.	300
19-23 January 2020	Basin	Ull de Ter Molló S. Joan de les Abad. Sant Pau de Segúries Embalse de Sau Viladrau Girona Cassà de la Selva Torroella de Montgrí	214.6 283.3 267.5 402.7 353.5 425.8 242.9 281.3 110.5	Ripoll Roda de Ter Girona Colomers Torroella de Montgrí	311.63 636.54 n.d.	456.73 1,178.80 1,080 1,300 1,000.8

*Daily average flow; ** Maximum recorded flow; *** Average annual flows since the completion of the Susqueda reservoir (in m^3/s): Sant Joan de les Abadesses (6.41), Ripoll (9.8), Roda de Ter (17.15), El Pasteral (10.82), Girona (13.63), mouth (26.6). Source: Consorci del Ter and Fundació AGBAR (2004). Own elaboration from Servei Meteorològic de Catalunya (SMC) and local observers (precipitation) and Agència Catalana de l'Aigua (ACA) (river flows)

4.2. Exposure

In the Ter basin, exposure to floods has been increasing during the last century. Population growth and agricultural, industrial, and especially urban expansion in flood prone areas appear to be the main causal factors. Between 1900 and 2019 the population of the Ter basin has more than doubled, growing from 177,000 to 454,000 inhabitants (Table 3 and Figure 2). The increase in urban density and its configuration along the Ter River and its main tributaries has led to a progressive concentration of the population in urbanized floodplains. While in 1900, half of the population concentrated close to the Ter and its tributaries, in 2019, almost three quarters of the population of the basin lived in these areas.

Table 3: Population change in the Ter sub-basins (1900-2019)

	Upper Basin	**Middle Upper Basin**	**Middle lower basin**	**Lower basin**	**Total**
1900	25,974	59,216	69,496	22,885	177,571
1910	27,677	62,201	74,769	23,983	188,630
1920	29,220	66,679	78,664	23,897	198,460
1930	29,907	72,353	86,392	23,233	211,885
1940	27,364	71,331	93,343	22,413	214,451
1950	29,319	74,595	95,309	22,878	222,101
1960	30,821	83,368	105,912	23,397	243,498
1970	30,220	96,645	129,101	26,010	281,976
1981	29,445	106.653	175,927	26,837	338,862
1991	26,938	108,675	162,515	28,171	326,299
2000	26,121	114,986	175,008	31,718	347,833
2010	26,580	138,890	228,462	39,883	433,815
2019	25,087	146,179	243,095	40,072	454,433

Own elaboration from IDESCAT

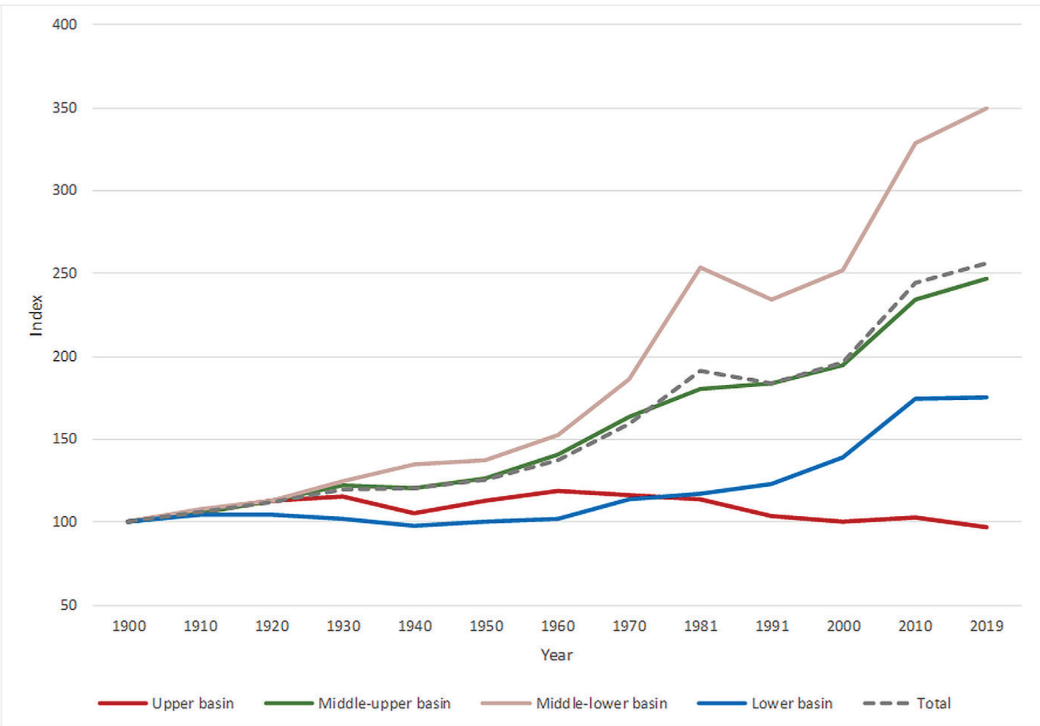

Figure 2. Population change in the Ter River Basin 1900-2020. Total and sub-basins (1900 = 100). Own elaboration from IDESCAT data

However, population, industrial and urban growth is also characterized by notable spatial and temporal differences. As in the rest of Catalonia, the first third of the 20th century was marked by the intensity of the industrialization and urbanization processes in the upper and middle basin where numerous textile mills took advantage of the hydraulic resource potential of the river and tributaries. Metal works, paper and tanneries, and hardware proliferated in towns such as Ripoll, Torelló, Manlleu and Girona. In the lower basin, the crisis brought about by the philoxera pest that ruined vines in Catalonia damaged the important cork industry of the area while agricultural development remained limited. On the other hand, however, the road and railway networks expanded improving considerably communications with Barcelona and France as well as communications along the river course.

The economic and social crisis caused by the Spanish Civil War and the post-war period severely affected industrial occupation and slowed rural exodus, so that demographic and urban growth until the late 1950s was weak in most of the basin. The 1940s and 1950s were thus characterized by slow or stagnant economic growth although some sectors (especially textile centers) could benefit from their privileged position within the Spanish autarchy system. The strategic change of the Spanish economy abandoning autarchy and embracing liberalization and openness at the end of the 1950s inaugurated an era of rapid economic growth in Catalonia which again translated into population, industrial and urban expansion in the Ter basin. Fueled by migration from Southern Spain, population in the basin grew from the 243,000 inhabitants in 1960 to 338,000 in 1981; that is, an increase of almost 30% in 20 years. Growth, however, was uneven. Demographic and economic stagnation began to extend in the upper basin where traditional manufacturing was hit hard by the crisis and restructuring of textiles. In the rest of the basin the industrial base diversified from textiles to new sectors, especially food processing, and metallurgical and chemical production while mass tourism expanded along the coast. The 1970s brought about the definitive crisis for the textile sector along with the closure and abandonment of many mills located in the main river courses, especially in the upper and middle-upper basin. Cities such as Vic, Girona and Banyoles survived the crisis by reinforcing the specialization in food processing and above all by a strong shift towards the service economy. On the other hand, the definitive specialization of the lower basin in mass tourism insulated the area from the effects of economic restructuring during this period at the expense however of a rapid and intense occupation and transformation of flood prone land.

The 1990s and especially the entry of the 21st century, inaugurated a new stage of demographic and urban growth. The process of population concentration in the main urban centers located along the Ter River and their areas of influence continued to increase. In the upper and middle basin, about three quarters of the population is concentrated in a few municipalities, most of them close to the river or tributaries. In the lower basin, two municipalities absorb about half of the population, but others on the coast see their numbers increase exponentially during summer. Beyond any doubt, tourism has been the main activity driving the economy of most of the basin. In the upper basin snow and mountain tourism has taken the role previously played by textile mills as the economic engine while in the lower basin sun and beach tourism is by far and large the dominant activity. Specialization in tourism and its different modalities has led to the proliferation of secondary dwellings, campsites, hotels, rural tourism houses and other tourist infrastructures and facilities, which have contributed to revitalize the stagnant economy of the upper basin and feed the expanding economy of the lower basin. Nevertheless, the expansion of tourism, urbanization and related infrastructures in floodplains and coast lines has also meant an increase in the exposure of people and goods to inundation. The construction of increasingly large and complex infrastructures and facilities (distribution centers for basic services such as water, energy, gas or telephones, distribution and logistics centers, fire stations, etc.) often located in flood prone areas and frequently affected by episodes of river flooding or by heavy rainfall represents perhaps the most visible example of this increasing exposure to floods.

To summarize this historical overview on exposure in the Ter River basin, it is estimated that the land to be flooded by events with a return period of 500 years is approximately 15,230 hectares (ha) or 4.65 percent of the total area of the basin, of which urban land represents 1,480 ha or 10 percent of the total land at risk of flooding. This figure is below the Catalan average estimated in 15 percent (Vilaplana, 2008; Saurí, 2011) (Table 4). The largest flood prone area is in the alluvial plain of the Ter River, in the middle-lower basin (5.16 percent of the total area is at risk of flooding) and the lower basin (about 25 percent at risk of flooding). Except for the cities of Girona, la Bisbal d'Empordà and Torroella de Montgrí-l'Estartit and their peripheries, most of the area potentially affected by flooding is agricultural land. Urban land in areas at risk of flooding is larger in the upper and middle-upper parts of the basin (between 21 and 25 percent of the total) than in the middle-lower part (between 8 and 10 percent) and the lower part (between 3 and 5 percent), which is explained by the higher urban densities along the Ter River and its tributaries found upstream of the reservoir system.

Table 4. Land use zoning for areas exposed to the 500-year flood. Ter River basin 2019

Land Use Category	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Urban (consolidated)	1,129.7	7.42	181.14	22.73	369.61	20.29	367.2	6.85	211.6	2.92
Urban (non-consolidated)	53.6	0.35	10.69	1.34	26.49	1.45	9.12	0.17	7.29	0.10
Programmed urban (marked)	247.4	1.62	20.26	2.54	85.01	4.67	95.3	1.78	46.7	0.65
Programmed urban (non marked)	39.3	0,26	1.86	0.23	5.59	0.31	15.06	0.28	16.77	0.23
Non-urban	13,760.3	90.35	583	73.15	1,334.9	73.28	4,870.9	90.91	6,971.3	96.11
TOTAL IN Q500	15,230.3	100	796.95	100	1,821.6	100	5,357.7	100	7,253.9	100
TOTAL AREA (ha)	328,174	4.64	82,530	0.97	112,443	1.62	103,731	5.16	29,470.1	24.61

1 = area (ha); 2 = Percent within the 500 yr. flood; 3 = Upper Basin (ha); 4 = Percent within the 500 yr. flood; 5 = Middle Upper Basin (ha); 6 = Percent with in the 500 yr. flood; 7 = Middle Lower Basin (ha); 8 = Percent within in the 500 yr. flood; 9 = Lower Basin (ha); 10 = Percent within the 500 yr. flood.

Own elaboration from ACA (for the determination of the 500 yr flood) and Departament de Territori i Sostenibilitat de la Generalitat de Catalunya (for land use categories).

4.3. Susceptibility

In this article two main types of susceptibility to floods are singled out: human and social susceptibility, related to factors that may intervene in the loss of human lives, and functional and economic susceptibility, related to the characteristics of the different socioeconomic activities that may influence the possibilities of suffering damages. Human and social susceptibility depend both on the magnitude of the event and on intrinsic (age, income, gender, perception, knowledge, physical capacities of individuals, etc.) and extrinsic (effectiveness of protection/prevention measures, capacity for recovery, etc.) characteristics of people exposed. Functional and economic susceptibility is related to the various socioeconomic activities present in affected areas. It depends on the level of damage to economic activities, property, infrastructures, and the capacity of society to restore the normal operation of interrupted or disturbed activities.

4.3.1. Human and social susceptibility

One remarkable finding in the characterization of flood impacts in the Ter basin is the very low number of catastrophic episodes with human victims. In fact, of the nine episodes selected for analysis only one that of October 1940, stands out in terms of human deaths while the rest (except for one death in the episode of 1932) do not register human casualties. This is rather unusual in the recent history of flood events in Catalonia and Spain where a consistent reduction in the number of human victims caused by floods in the last decades does not rule out a certain number of deaths even for relatively small episodes.

At any rate, deaths caused by floods of the Ter and its tributaries have occurred mostly in the homes themselves, where people drown, are swept away by the flow or are crushed by rubble provoked by crumbling walls and roofs. This was the norm in historical episodes such as those caused by the Galligants River in Girona (September 18 and 19, 1843, approximately 115 human victims) or the Mèder in Vic (8th of October 1863, a hundred dead). As said, for the period studied, the episode that caused the largest number of human victims was the so called "*Aiguat de Sant Lluc*" (October 17-20, 1940), with some 80 deaths in the Ter basin, 61 of which in Torelló, 10 in Manlleu (in the middle-upper basin), and the rest in Girona (Table 5).

Table 5. Documented human and economic losses

Episode (year)	Human victims	Economic losses* (Ter Basin)	Economic losses* (Girona province)
1919	0	30.700 PTA in the town of Verges (agriculture)	n.d.
1932	1 (Girona)	n.d.	2 million PTA
1940	80 (71 in Manlleu and Torelló and the rest in Girona)	n.d.	120 million PTA (Ter, Fluviá and Muga basins).
1962	0	150 million PTA	162 million PTA
1970	0	500 million PTA in Girona	600 million PTA
1982	0	900 million PTA	n.d.
1994	0	n.d.	1 billion PTA
2020	0	7,6 million euros (between Girona and Torroella de Montgrí-Estartit)	100 million euros

* Losses in PTA (peseta was the name of the Spanish currency before 2002). Losses correspond to PTA of each year and are not corrected for inflation.
Own elaboration from technical reports and memoranda, and press clips.

The analysis of who died in this episode reveals the importance of housing characteristics (location, quality of construction, state of conservation, etc.) which, in turn, are closely related with wealth. Most of the people who died in Torelló and Manlleu were low income residents who lived in old housing located near the river built with generally low-quality materials (earthen walls) and therefore highly susceptible to the ravaging effects of floodwaters. However, in Girona, most of the deaths were caused by the collapse of a bridge where many people had concentrated to watch the flood wave of the Güell River. Human negligence and the failure of authorities to prevent such risky behavior were already a factor which will become more important in the following decades. In conclusion, mortality caused by floods of the Ter and its tributaries during the period of study is concentrated almost exclusively on the single catastrophic episode of October 1940, the most important in terms of rainfall and flows recorded in the basin, and which took place right after the end of the Spanish Civil War under very difficult social and economic conditions for most of the population in the basin.

However, human and social vulnerability increases significantly in some of the catastrophic episodes analyzed, considering the number of people affected, either because they have suffered physical impairment (injuries, mental illnesses) or because they have lost part or all of their properties.

In episodes such as those of 1940 or 1962, social inequalities strongly influenced the susceptibility of different social groups and their limited responses to the flood. Thus, many of those affected by the 1940 episode were industrial workers in factories located in towns such as Ripoll, Manlleu, Torelló, or Salt, that lost their jobs (Ribas and Saurí, 1993). In the 1960s, when it was necessary to build new housing in Campdevànol for groups with low purchasing power, two blocks of houses for this purpose were built in an area flooded by the 1940 episode (Codinachs, 1994). Another example is the more than 500 immigrants, mostly from Andalusia, who had to leave the "Río" neighborhood in Girona, after the flood of October 1962 devastated the self-built shacks occupying the same bed of the Ter River (Ribas, 1994). In all these cases, the need to ensure a facility as basic as housing explains the occupation of flood prone spaces, that is, spaces where the value of the land was low or simply zero.

4.3.2. Economic and functional susceptibility

In general terms it can be argued that, for the whole of the Ter River basin, economic and functional susceptibility to floods exceeds, in economic terms at least, human and social susceptibility. Although we are not able to express figures of economic losses in constant values, Table 5 reflects a tendency towards an increase in the amount of economic losses in each new catastrophic flood episode analyzed. However, the levels of economic and functional vulnerability vary depending not only on the magnitude of the episodes but especially on the degree of impact and recovery capacity of the economic activities and infrastructures characteristic of each territorial model for each historical period.

During the first part of the study period (1900-1935), two clearly differentiated models of territorial organization can be identified: an agrarian-based model in the lower basin and an agro-industrial model combined with urban-services in the rest. In the lower basin, agriculture is the most susceptible productive sector of the period. The floods of 1919, and especially 1932, destroyed much of the cereal and fodder crops of the alluvial plain and caused severe damage to riverbank tree plantations. Irrigated infrastructures (Sentmenat canal and the Canet protection wall) were especially affected and some towns remained isolated for days due to damages to roads and highways. The rapid reconstruction of impaired irrigation infrastructures and the management of changes in course and direction experienced by the riverbed that occurred after each flood would be the most important demands raised by farmers since these impacts often meant the interruption of production cycles for more than one year. The conservation of traditional forms of settlement in the highest elevations of the floodplain would explain the low impact of floods on homes and buildings (Saurí *et al.,* 1993).

The agro-industrial model, combined with the urban/service economy of the rest of the basin, explains why industry and services were the most affected economic sectors in this period. Since the end of the 19th century and into the first third of the 20th, the Upper, Middle-upper and Middle-lower sub-basins saw the installation of factories and industrial estates and the development of the road network (roads and railways). Consequently, hydroelectric power plants, factories, and industrial channels in towns such as Ripoll, La Farga de Bebié or Bonmatí were heavily affected by the episodes of 1919 and 1932. Also, railway, bridges, roads and highways were hit by landslides. Cities such as Manlleu, Girona or Banyoles, which during these years experienced significant urban development, also suffered high damages to industries, shops and urban services, such as the electricity supply.

The Spanish Civil War represented the starting point of a context of great economic precariousness that will characterize much of the second period under study (1936-1969). In a context of post-war economic and political crisis, economic and functional susceptibility to floods grew throughout the basin. Autarchy and interventionism inspired economic policy in the early years of the Franco government and reverted into minimal capital investment in the industrial base of the Ter basin which, on the other hand, had experienced a considerable dynamism between 1914 and 1936. With the industrial base reduced, agriculture and informal tertiary services became refuge activities for a depauperated population. It is in this context that on October 17 and 18, 1940, one of the most catastrophic floods in the history of the Ter River took place, attributable not only to rainfall amounts of a "monsoon" intensity (around 1,000 mm in 24 hours in the Vallespir region), but especially to the economic and social context of the period. In total, in the Girona province, 90 deaths, 58 destroyed bridges, 25 kilometers of seriously damaged roads, damages to 165 industries, 149 businesses, 230 urban farms and some 174,192 flooded hectares of cultivation were recorded. Economic losses at that time were valued at 120 million pesetas, an exorbitant figure for the period (Ribas and Saurí, 1993). Industrial activity was one of the most affected sectors. Many of the yarn and knitwear textile factories, metallurgical workshops, food processing factories, etc. in towns such as Torelló, Manlleu, Ripoll, Roda de Ter, Angles or Salt, but also many of the dams and canals that made possible the production of the energy necessary for their operation, were seriously impaired and many of the workers were left unemployed. Damages of the built environment were extensive in Girona due to the combined effects of the Ter and its tributaries Güell and Onyar. In the lower basin, the river broke levees at various points and tried to recover its old course, joining its waters with those of the Fluvià River. Material losses concentrated in crops and livestock.

However, the high economic and functional susceptibility of the Ter basin during this episode was not only translated into severe damage to economic activities, properties, infrastructure, but also reflected to the low capacity of society at the time to restore in time interrupted or disturbed activities. Damaged hydraulic control works were rebuilt, but no new flood control infrastructure was constructed or plans preventing the continued use of floodplain areas approved.

The economic and social context of the Ter basin began to change in the second half of the 20th century, following a process of rapid transformations, lacking, however sufficient resources and democratic governance. These transformations accentuated the differences between a traditional agro-industrial model in decline (especially in the upper basin) and an urban/ tourism/services model that was gaining prominence in the middle and lower basin. Immigrants from Southern Spain continued to arrive in large numbers occupying flood prone areas of the expanding cities. It is in this context of urban-industrial expansion that up to 11 flood episodes were registered in the Ter basin in the 1960s, two of them catastrophic (October 11 and 12, 1962; September 13, 1963). Both episodes affect most the Middle-lower and Lower basins, especially the city of Girona and its neighborhoods of Sant Narcís, Santa Eugenia de Ter or Río built on the very same bed of the river Ter (1962). Workshops, warehouses, factories and shops, and water and electricity facilities suffered the greatest impacts. The lower basin, which until the late 1960s maintained a distinctive agrarian model, also suffered from the effects of these episodes. Floods occurred almost every year in the 1960s causing serious inconveniences to agriculture and livestock, as well as damages to roads and highways. The persistence of the problem of floods during this period of strong economic development and increases in the standard of living explains the repeated complaints and demands of farmers, commercial interests and local administrations (from the municipalities to the provincial councils) for the construction of flood control works in Ter and its tributaries, but especially for the construction of the long promised reservoirs in the middle section of the river.

The inauguration of the Susqueda reservoir in 1969 marks a turning point regarding flood control in the Middle and Lower basin. Reservoirs exerted an unquestionable containment effect on floods downstream which explains the decline in episodes during the 1970s. In the period 1970-1985 there were two catastrophic flood episodes (October 11 and 12, 1970; and November 8, 1982) both exemplifying the changes in exposition and susceptibility derived from the territorial re-functionalization of the Ter basin, especially in the Lower and Upper basins, brought about by tourist activities. In the Upper basin, tourist activities occupied and transformed flood prone areas previously under extensive land uses such as cattle grazing. The flood of November 1982 hit especially hard ski resorts, campsites, weekend and vacation homes, and the burgeoning urban commercial sector of the Upper basin. Together with agriculture, which remained strong especially in the Middle and Lower basin, tourism suffered the largest materials losses of this period. On the coast, the rapid and intensive urban growth of l'Estartit through new residential areas (Griells, la Pletera, Salats), campsites (Delfín

Verde, la Sirena, etc.) and golf courses (Gualta and Pals) often on flood prone land, explained the dramatic increase in flood losses that will continue in the following decades.

However, the most catastrophic episode of this period affected the city of Girona. In this episode, however, the Ter River only played a secondary role, since the Sau-Susqueda-el Pasteral reservoir complex was able to contain successfully floodwaters from upstream. Two small rivers in the city, the Onyar and the Güell, were the main causes of a flood that inundated more than 75 percent of Girona. Although no deaths were recorded, economic losses were the highest in the history of the city. The most distressed sectors were industrial and commercial establishments. In total, 2,000 of these establishments were damaged with losses amounting to 85 million pesetas. Public services (gardens, drinking water infrastructure, schools, hospitals, etc.) also experienced extensive impacts. Houses and buildings in the flooded area were also hit as were roads and streets and the flood walls of the two rivers. In addition, the flood damaged or ruined about 500 vehicles.

In the 1980s, the Ter basin continued to suffer catastrophic flood episodes, without human victims, but with high economic losses and extensive disruption of normal activities. The 1990s were marked by the episode of October 10 and 11, 1994, which concentrated in the tourist center of l'Estartit, and aggravated by landslides that destroyed residences, hotels and roads. On this occasion, the cause was not the Ter itself but the intense rainfall that fell on the Northern coast of Catalonia. This "pluvial" flood was already interpreted at that time by local meteorologist Josep Pascual as a clear example of change in precipitation patterns in the Mediterranean coast that appeared to indicate an increase in high intensity events (Pascual, 2005). L'Estartit is also a manifestation of a rapid increase in exposure to the risk of flooding after the continuous occupation of the Ter floodplain for tourist related infrastructures and services. However, the town has managed to mitigate relatively rapidly the negative consequences of flooding, and the rate of flood losses appears to fall behind the rate of economic growth. In other words, the level of wealth generated in coastal floodplains may revert to a decrease in vulnerability to floods (Ribas and Serra, 2009).

Finally, the storm Gloria of January 2020 illustrates the susceptibility of productive sectors and infrastructures increasingly linked to tertiary activities and services and public infrastructures, which have gained prominence throughout the basin. In the upper Ter, towns historically hit by floods such as Ripoll and Vallfogona del Ripollès suffered the worst consequences of the event, with damages to roads and railways, water supply systems, sports halls and urban infrastructure. In the Middle upper basin, the most important damages were on the railway line in the Vic-Ripoll section and on local roads as well as on water treatment plants that left towns like Manlleu without drinking water during hours. However, the most important damages occurred in the Middle-lower and lower basins, where the flood forced the population of 26 municipalities to be evacuated or confined.

In the Middle-lower basin, the city of Girona had to deal with the overflow of the Ter, causing important damages to public infrastructures and facilities (sports halls, football fields, schools, the city hospital, the auditorium), electricity supply systems and drinking water networks, urban furnishings, and communications. As a novelty compared to previous episodes, promenades and urban and peri-urban green infrastructures on the riverbanks that in recent years had been conditioned as leisure areas for hikers and cyclists, were also impaired. In the lower basin, besides the persistent impacts on roads, floods also damaged the highly technified agriculture of fruit orchards and its supporting infrastructures (irrigation channels, access roads, etc.), as well as campsites, promenades and beaches. The flooding of the drinking water treatment plant meant that the towns of Torroella de Montgrí and l'Estartit lacked potable water for three weeks.

In the coastal municipalities of the lower basin, the floods of 1994 and 2020 encountered a population less susceptible to the impacts of extreme events due to higher levels of public and private wealth which facilitated a quicker recovery from losses compared to previous episodes. In the lower Ter, where the storm Gloria harmed some 12,000 hectares of agricultural land, especially cereals and apple trees, aid packages and low-interest loans to farmers from contingency funds were rapidly implemented. Similar circumstances occurred in localities hit by the storm Gloria, such as the city of Girona or l'Estartit, where the municipality assumed, in the first instance, the expenses derived from the cleaning of river courses and beaches in order to restore them as soon as possible. Applications for aid were subsequently processed to the regional and national governments to cover for the damages caused.

4.3.3. Adaptive capacity

Along with the important territorial transformations experienced by the Ter basin and the impacts of the catastrophic floods that occurred during our period of analysis, adaptation to floods has also changed. Traditional adaptation had usually consisted in avoiding flood-prone land for permanent settlement, and, in fact, this form of adaptation prevailed in the lower basin well into the 20th century. Population settlements tended to locate on river terraces or in the foothills of the Montgrí mountain and away from the alluvial plain (Barbaza, 1988). The construction of lateral earthen levees remained until the mid-20th century the only major hydraulic infrastructure designed to protect farmland from river flooding. After the catastrophic floods of 1919 and 1932, the local authorities of the lower basin requested the embankment of the Ter and the Daró rivers, to protect agricultural land and road infrastructures. By way of example, after the flood of 1919, the Ter Municipal Association was created, bringing together all the riverside municipalities of the Middle-lower and Lower basin, to claim the embankment of the Ter from the Pasteral area to the sea, which has not been implemented (Saurí *et al.,* 1993).

In the rest of the basin, the agro-industrial model combined with the urban/services model had already facilitated the installation of factories, industrial estates and permanent population settlements in the vicinity of the river courses. Therefore, the biggest economic and material losses from catastrophic episodes were from buildings and industrial and urban infrastructures. This would explain why projects and actions to control flooding appear relatively early in the period.

Table 6 includes the main hydraulic infrastructures built in the Ter basin. The flood of October 1940 caused a rapid reaction by the Francoist authorities. The General Directorate for Flooded Regions was created to plan and execute post-disaster recovery actions. However, the economic precariousness of the moment and the lack of flood planning and management policies implied at best, just the reconstruction of hydraulic infrastructure that had been damaged (Ribas and Saurí, 1993). It was not until the 1960s that the persistence of the problems and a greater financial capacity by the state made possible the construction of large flood control works, among which the Susqueda reservoir (1969) and the opening of a new channel for the Daró River in the lower basin. The floods of October 1970 also motivated the materialization of many flood control infrastructures in Girona (Ribas, 1994, 2007 and 2009). The 1982 floods in the upper basin, led to the construction of containment dykes at the headwaters of the Ter, designed to protect population centers downstream. Since the mid-1980s, no major new hydraulic works have been built in the Ter basin, despite the fact that these are often demanded by the population and local councils to regional and national authorities (Roset *et al.*, 1999). Pending projects, such as the construction of reservoirs in the headwaters of the Onyar River in Girona, have to face not only budgetary restrictions but also a certain change of perspective on the problem of flooding inspired by the principles of the European Directive on Floods (Directive 2007/60/EC). The Directive recognizes that floods are impossible to eliminate and, therefore, that societies must learn to “live with them” (Olcina *et al.*, 2016). Both because of European mandates and for financial constraints, the Catalan Water Agency appears to be embracing these new perspectives on flood management.

Table 6. Main flood control infrastructures in the Ter River basin (1900-2020).

Flood control infrastructure	Location	years
Sau Resevoir	Middle upper basin	1949-1963
Embankment of the Ges River (Torelló)	Middle upper basin	1946-1956
Diversion of the Daró River from Gualta until the Ter River	Lower basin	1960-1970
Susqueda reservoir	Middle upper basin	1963-1968
Channelization of the Onyar River (Girona)	Middle lower basin	1963-1966
Diversion and channelization of the Güell River (Girona)	Middle lower basin	1964-1968
Flood walls of the Ter River (Manlleu)	Middle upper basin	1968-1987
Dredging and embankment of the Onyar River (Girona)	Middle lower basin	1970-1971
Colomers reservoir	Lower basin	1970
Embankment of the final course of the Ter River from the Daró confluence until the sea	Lower basin	1971-1973
Levees and flood walls in several towns (Camprodon, Ribes de Freser, Campdevànol, Ripoll, Setcases, etc.)	Upper basin	1983- 1998

Own elaboration

Other measures, such as land use planning in floodplains have proven to be difficult to implement. Urban planning prevailing in municipalities during the Franco years ignored the regulation of land uses in floodplains. With the advent of local elections in the late 1970s, the first urban plans aimed at a certain but still timid, control of growth in these areas. Urban development laws promulgated by the Catalan government have incorporated the risk of flooding as an element to be taken into account in the zoning of new uses in municipal plans. The decade of the 1990s was prolific in the elaboration of cartographies of flood risk by the ACA that are of mandatory consultation in local urban planning. However, the actual implementation of these policies has not always been positive, and areas subject to flooding either from river flows or from rainwater continue to be occupied and transformed. The situation is further complicated in spaces coveted by new urban or tourist developments in some parts of the Ter basin (especially the upper and lower basins). Fortunately, more and more examples can be found in the opposite direction. In recent years, the LIFE Pletera project has been implemented in l'Estartit (one of the towns most exposed to floods and storm surges). This project involved the de-urbanization of flood prone land and the restoration of the previous wetland system (Pueyo-Ros *et al.*, 2017 and 2018). Restored wetlands were able to absorb flooding during the Gloria episode of January 2020.

Throughout the study period it can be noticed how post-catastrophe aid is increasingly assumed by public institutions. In the aftermath of the disaster, this aid usually came from spontaneous charity campaigns as well as from local and regional public authorities. Relief Boards were created in order to coordinate immediate assistance and, subsequently, commissions in charge of assessing damages were also established. In the medium and long term, and especially for those episodes with greater impacts, aid was increasingly the responsibility of national institutions, either by enacting enabling financial measures (exemption or moratoria on the payment of taxes, low or no interest loans, etc.) or through direct compensation packages or the coverage of expenses associated with the reconstruction of public services and infrastructures. Laws intended for very extreme events have used the legal figure of "catastrophic zones" by which all public and private losses are assumed by the state. Furthermore, in Spain, the creation in 1954 of the Consortium for Insurance Compensation (*Consorcio de Compensación* *de Seguros*) guarantees practically universal coverage for floods and other natural risks. The Consortium allows for a minimum of security regarding the recovery of losses caused by floods, which contributes to reducing the relevance of these losses in times of economic difficulties. The evolution of the amounts paid by the Consortium during the last decade indicates not so much an increase in the frequency and impacts of extreme natural phenomena as a greater penetration of insurance and, above all, an increasing accumulation of goods and services in areas of risk (Saurí, 2011). For example, in the Ter basin, the episode of intense rains in June 2000 in the city of Girona generated losses of around 3 million euros in insured damage, including damage to 200 shops and offices, 250 homes and 125 cars (Ribas *et al.* 2020).

Forecasting and warning systems on extreme precipitation and floods have improved enormously during the period of study, hand in hand with continuous technological progress and greater organizational capacity and availability of human and material resources to deal with emergencies. In the Ter basin emergency management in the event of a flood episode is based on both collective and individual behavior and practice of people living in flood prone areas and from the practices planned by local and regional administrations. During much of the 20th century, solidarity mechanisms and the transmission of knowledge between generations on the precautions to be taken under the threat of a flood (church bells ringing to warn of imminent danger, construction of walls at the entrance of houses to prevent the penetration of water, the transfer of the most valuable belongings to the upper floors of the buildings, etc.) turn out to be many times sufficient for less catastrophic events. In cities like Girona, recurrently hit by floods, some of these individual and collective emergency management systems were certainly useful. For example, since at least the eighteenth century, inhabitants of the lower areas of the old town built doors through dividing walls between buildings at the height of first floors, so that people could move from one building to another and escape danger in times of flooding (Ribas, 1994 and 2009). This peculiar emergency action lasted in Girona until the middle of the 20th century.

Flood warnings from upstream the rivers were practically non-existent until the beginning of the 1930s when the use of the telegraph and telephone became widespread (Díaz, 1989). Since the 1970s these systems have undergone significant progress. Flow and precipitation measurement equipment was extended and improved (the entry into operation of the Sau and Susqueda reservoirs in the 1960s made available information on flow rates upstream of Girona), and the number of collaborators in alert tasks increased (in 1962 the River Nursery Corps was created). However, meteorological and hydrological forecasting systems continued to be too generic and little precise. In the late 1980s, the Automatic Hydrological Information Service (SAIH) was installed and perfected until it became an automated data transmission system for rainfall and river flows in real time. Despite all these advances, short and medium term meteorological and hydrological forecasting remains difficult. In the last catastrophic episode of January 2020, uncertainty of the forecasts prevented the ACA to release more water from the reservoirs before the storm so the rapid accumulation to risky levels forced larger releases of water that caused inundations downstream (La Vanguardia, 24/1/2020).

Finally, at the beginning of the 1980s, the Generalitat of Catalonia and the municipalities promoted the drafting and implementation of emergency plans at regional and local scales. In the Ter basin, most municipalities have flood emergency planning, although with very uneven states of updating and implementation. The storm Gloria highlighted positive aspects of emergency planning such as the work carried out by Civil Defense personnel, firefighters, rural agents, volunteers and the media. Some aspects needing improvement must be mentioned as well. First, the little information available to the mayors of the small towns in the Middle lower and Lower basin about the development of the flood wave. Second, the early lifting of confinement in some towns when the most important flood peak had not yet arrived. And finally, the curiosity inherent in the human condition, turning dangerous events into spectacles, must be mentioned. Many people, unconscious and reckless, accumulated near the river courses, the bridges or under riverside trees at risk of falling due to the storm (Feliu, 2020).

5. Discussion and conclusions

Results of the historical analysis of catastrophic flood episodes in the Ter River basin appear to confirm the decrease in long terms vulnerability to flooding reported for Europe and elsewhere (Neumayer and Barthel, 2011; Jongman, 2015; Prapotny *et al.*, 2018). The breakdown of vulnerability into the three components proposed by the IPCC (exposure, susceptibility and adaptive capacity) has proven a useful framework for explaining this trend. In the Ter River basin exposure to flooding has increased significantly in the last 100 years. While the relationship of this rise with a parallel growth in the frequency and magnitude of floods (possibly linked to climate change) cannot be ruled out, as the Gloria episode of 2020 would suggest, it seems more likely that exposure has increased after the continuous occupation, transformation, and accumulation of material wealth in flood prone land (Barredo, 2009). Hence the steady trend in increasing economic losses characteristic of the Ter basin. Although conclusive evidence cannot be provided due to the paucity of data and lack of specialized economic studies on flood impacts, it is highly likely that losses compared to the evolution of regional GNP (Barredo *et al.*, 2012) would show also a declining trend. The evolution of wealth related indicators such as GDP or Per Capita Family Income in most municipalities included in the flood risk areas of the Middle lower and Lower Ter Basin (ACA, 2019) shows an upward trend, always above average Catalan figures (Ribas and Saurí, 2002; IDESCAT, 2019).

In the study area individual and social susceptibility to flooding appear to have declined mostly through advances in human welfare and better conditions in work, housing and general standards of living than in the past. Regarding social susceptibility, the increase in material wealth and in democratic governance, among other social gains, has also ensured a diminishing susceptibility to flood impacts. In terms of adaptive capacity, the Ter River case exemplifies the progressive construction of a comprehensive flood management approach in which large flood control works (reservoirs, embankments, channelization, etc.) still play a dominant role in protecting people and goods from extreme events. However, progress in flood forecasting and warning together with emergency planning has been also remarkable and helps to explain why events of a large magnitude such as Gloria do not cause human casualties. Post disaster relief measures have also improved especially through the generalization of insurance (Kron, 2015). As a result of this progress, flood management in the Ter River basin is becoming more comprehensive, more diversified and more complex as well.

However, many challenges remain. Perhaps the most important is the role of land use planning in reducing exposure. Partly inspired by the Dutch experience, the flood Directive of 2007 introduced a fundamental change in flood management. Admitting the impossibility of suppressing these phenomena with hydraulic works, the Directive adopted the principle of “living with floods” or the need of rethinking the role of large flood control infrastructures and their economic, social and environmental impacts and put a greater emphasis land use planning in floodplains. The Dutch program of “Room for Rivers” represents an example of removing intensive human occupation of floodplains and returning to the river system spaces that not only help to dissipate flood waves but that harbor significant environmental values and services (Warner *et al.*, 2013; Ollero *et al.*, 2015). Still, floodplains are coveted for development and land use plans restricting exposure are difficult to accept especially at the local level because the benefits of development are perceived to be greater than the risks (Lara *et al.*, 2010). In the Ter River, post recovery action after Gloria has been primarily aimed at reconstructing infrastructure and other assets that permitted the continued occupancy of floodplains in the lower basin missing the opportunity of alternative approaches in flood management, most notably the de-intensification of land uses (Rode, 2014).

At any rate, storm Gloria could imply a turning point in flood management because very clearly for the first time the event was associated to climate change. Moreover, the increasing recognition of floodplain ecosystems of spaces of value that need protection from development has also contributed to limit and occasionally revert intensive occupation as the Pletera project in the lower basin demonstrates. If after one hundred years it can be forcefully argued that society in the Ter River basin is becoming less vulnerable and more resilient to flooding perhaps it is time to direct the next management efforts to enhance the condition of resources that many times in the past floods have enjoyed and reduce their risk potential. Floodplains may offer multiple environmental and resource services to society if their ecosystems are in good state and able to provide economic value.

However, the line between resources and hazards in water is very thin as could be seen in the difficulties experienced by the Ter reservoirs in routing flows during Gloria. Before the event, water stored in the reservoirs was a resource to be used in hydroelectrical production, irrigation and water supply. The massive arrival of upstream flows from heavy rain meant that for security reasons reservoirs had to release water that caused unintended flooding downstream. If floods will become more likely under climate change, the challenge is not only to learn to live with them but also to appreciate the multiple benefits they may provide if properly managed. In the Ter basin and elsewhere in Catalonia, storm Gloria opened an important debate on this change of perception. However, barely a few weeks after the pandemic and the associated economic and social crisis will surely bring more pressures to continue with the existing state of affairs.

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UPDATED KNOWLEDGE ON FLOODS AND RISK MANAGEMENT IN THE MIDDLE EBRO RIVER: THE "ANTHROPOCENE" CONTEXT AND RIVER RESILIENCE

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ABSTRACT. The floods of 2015 and 2018 in the Middle Ebro River have led to a rethinking and updating of the forecasting and management systems. The improvements in the flow measurement systems applied in this type of extreme phenomena have led to questioning the values that were recorded in the past, officially changing the maximum flow rates of some historical floods. This has called for the need to update the knowledge/information of those recorded in the middle Ebro River, for example changing the return periods and making previous scientific studies obsolete. Updated data are applied, trying to re-characterize the floods of Ebro River since 1950, date in which the beginning of the "Anthropocene" is evident in the river management of the mainstream and its basin. At the same time, in the proposed risk management plans compliant with 2007/60/EC Directive, the structural measures are being replaced by more respectful and better adapted prevention systems for the river. The two processes interact and are essential for educating the population on risk, adopting preventive measures that are sustainable and consistent with the authentic (corrected) characteristics of the river and its floods. Thus, scientific knowledge has been consolidated as a tool to display corrected data, or, the river's updated reality, and also to make the affected inhabitants aware of the need to follow new management protocols, focused on river resilience and social strategies.

Actualización del conocimiento sobre las crecidas y la gestión del riesgo en el Ebro medio: el contexto del "Antropoceno" y la resiliencia fluvial

RESUMEN. Las crecidas de 2015 y 2018 en el curso medio del Ebro han provocado un replanteamiento y una actualización de los sistemas de predicción y de gestión. Las mejoras en los sistemas de medición de caudal aplicadas en este tipo de fenómenos extremos han llevado a poner en duda los valores que se registraban en el pasado, modificándose oficialmente los caudales máximos de algunas crecidas históricas. Esto ha implicado la necesidad de actualizar el conocimiento sobre las constatadas en el Ebro medio, cambiando por ejemplo los periodos de retorno y quedando obsoletos los estudios científicos precedentes. Se trabaja con los datos actualizados tratando de re-caracterizar las crecidas del Ebro desde 1950, fecha en la que es evidente el comienzo del "Antropoceno" en la gestión fluvial del río y su cuenca. Paralelamente, en los planes de gestión del riesgo planteados en cumplimiento de la Directiva 2007/60/CE, se van sustituyendo las medidas estructurales por sistemas de prevención más respetuosos y mejor adaptados al río. Los dos procesos interactúan y son fundamentales para educar a la población en el riesgo, adoptar medidas preventivas sostenibles y acordes con las auténticas (corregidas) características del río y de sus avenidas. Así, el conocimiento científico se ha consolidado como una herramienta para mostrar los datos corregidos, es decir, la realidad fluvial actualizada, y también para sensibilizar a los habitantes afectados sobre la necesidad de seguir las nuevas vías de gestión, enfocadas en estrategias de resiliencia fluvial y social.

Key words: Flooding, discharge data, flood risk, global change, mitigation measures.

Palabras clave: crecidas, datos de caudal, riesgo de inundación, cambio global, medidas de mitigación.

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1. Introduction

Floods are essential hydrogeomorphological processes in the functioning of the river system. At the same time, they constitute a natural risk due to the socioeconomic conditions that processes such as bank erosion and flooding can generate. Therefore, scientific knowledge of river floods is essential for focusing and addressing risk mitigation measures. In recent decades, progress has been made in replacing traditional hard defense measures with others adapted to river dynamics (De Bruijn, 2005; Batica and Goubersville, 2016). The enactment in Europe of the Flood Risk Management Directive 2007/60/EC marked a major change in trend by promoting the integration of river and social resilience. This paradigm shift in the Ebro River management has been led by the Ebro River Basin Authority (henceforth CHE), first, by the preparation of Flood Risk Management Plan (henceforth FRMP) and, secondly, the progressive application of the Ebro Resilience River restoration strategy.

The Ebro River basin (85,000 km^2) is the largest of the Iberian Mediterranean basins. The Ebro mainstream has a total length of 930 km and its middle reach of 345 km, of free meanders in a large floodplain of 3.2 km in average width and 6.0 km in maximum width (Ollero, 1992). Therefore, the Middle Ebro River constitutes a unique fluvial space in the Iberian Peninsula due to its dimensions and its significant flooding risk. This singularity and representativeness as a great peninsular river, together with its permanent problem in risk management, justifies the selection of the Middle Ebro River between Logroño and La Zaida (Fig. 1) as study area. The average flow of the Ebro River in the study reach slightly exceeds 100 m^3 s^{-1} (106 m^3 s^{-1} at the Mendavia gauging station) between Logroño and the confluence with the Aragón River. When receiving this tributary from the western Pyrenees, it reaches 225 m^3 s^{-1} in Castejón. This flow is maintained up to Zaragoza (230 m^3 s^{-1}) and increases slightly up to 236 m^3 s^{-1} (Gelsa gauging station), in the last sector of this free meandering Ebro River reach.

Middle Ebro River has several sufficiently long and previously worked series of hydrological data (e.g. Ollero, 1992, 2010). However, at the end of 2019, the modification of some maximum flow values since 1996 in the different gauging stations was confirmed. The modified data series cover 23 hydrological years, from the 1996-97 hydrological year to 2018-19. Its modification was decided after the flood in April 2018 and responded to three factors: i) the finding that the flow measurements in the last two floods (2015 and 2018) were much more reliable than in all the previous ones; ii) the greater reliability of the Doppler measurement systems, which were implemented in 1996, making suspect that prior to that date the stage-discharge curve provided very large margins of error; iii) the confirmation of the malfunction of the Castejón gauging station (ID 9002) during floods, which produces a bypass of between 300 and 500 m^3 s^{-1} of flow on the left bank that cannot be measured, which was well documented in 2015 and 2018 (Horacio *et al.,* 2019). Consequently, the basin organization has ruled out the Castejón station for the analysis and decision-making (although it is still operating) due to lack of quality, replacing it with the Tudela station (ID 9284), which began its measurements in 2006.

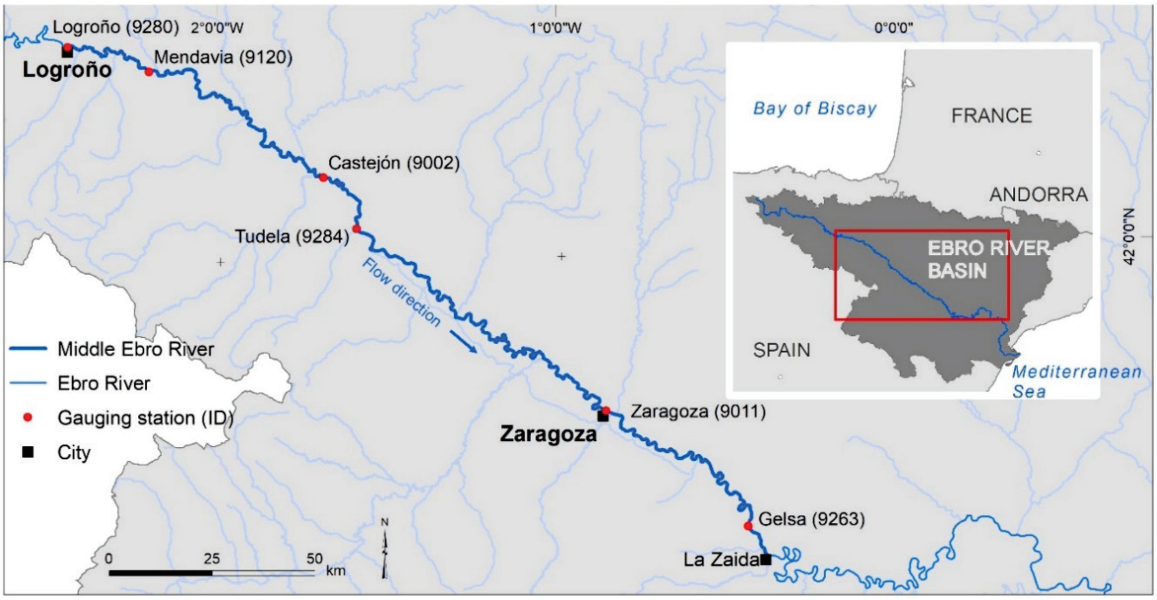

Figure 1. Location map.

The complex fluvial dynamics of the Middle Ebro River was considerably conditioned in recent decades by the global change in the basin, especially by human actions such as the regulation of flows or the defense against floods. Different researches (Ollero, 1992; Magdaleno, 2010; Ollero *et al.,* 2015; Díaz Redondo *et al.,* 2018) concluded that throughout the second half of the 20th century there was a significant transformation of the fluvial functioning due to anthropic factors. It can be stated that the "Anthropocene" manifests itself in the Middle Ebro River through a great acceleration of human intervention between 1950 and 1990. Hydrological data, continuous since 1950, and aerial images, allow us to clearly verify this process (Ollero, 2010).

The objectives of this work focus on i) updating the information on the floods of the Middle Ebro River, ii) explaining its evolution based on the new data available, and iii) evaluating the changes in its management since the beginning of the "Anthropocene", ~1950 (Waters *et al.,* 2016), to nowadays.

2. Material and methods

Hydrological information used comes from the Information System of Flow Discharge Yearbook (source MITERD –Spanish Ministry–) and the modifications introduced by the Hydrology and River Channels Area of the CHE. The modified and already validated data have been obtained directly from the aforementioned service, as they are not yet published. The complete series since 1950 of Castejón (ID 9002) and Zaragoza (ID 9011) gauging stations, and partially those of Logroño (ID 9280), Mendavia (ID 9120), Tudela (ID 9284) and Gelsa (ID 9263) have been studied. The Tudela series has been considered to be excessively short, so the Castejón data have continued to be used for different analyses. Working with historical floods (i.e. prior to 1950) has been discarded due to the low reliability of the data and the existence of gaps in the series.

The workflow of the article is structured in two simultaneously developed stages. The first one focuses on everything related to hydrological (mainly) and sedimentological analysis, while the second one refers to interventions on the Middle Ebro River reach.

Regarding the first stage, the hydrological events that reach the bankfull flow or overflow threshold in both Castejón and Zaragoza, or at least in one of them, have been considered as flood. The bankfull flow is a difficult parameter to identify and calculate in a channel of the dimensions and complexity of the Middle Ebro River. In the research corresponding to Ollero's doctoral thesis (1992), based on his own field observations and interviews with CHE technicians, an overflow threshold of 1800 $m^3 s^{-1}$ was established in Castejón gauging station, whereas 1600 $m^3 s^{-1}$ in Zaragoza gauging station. This value can be used for the old series (1950-1996), but it is no longer valid for the current one (since 1996 and ongoing). New field observations in recent floods and interviews with technical personnel of the CHE, as well as an unpublished research report (Martín Vide, coord., 2018), establish that this flow (series 1996-2019) should now be located at ~1750 $m^3 s^{-1}$ in Castejón and ~1500 $m^3 s^{-1}$ in Zaragoza.

The interpretation of the hydrological data was accomplished using a simple statistical treatment of mean and extreme values, equivalent to that performed in previous studies (Ollero, 1992, 2010; Sánchez Fabre *et al.,* 2015, 2017). For the return periods, the Gumbel method was used, as in the same previous studies and in the internal reports of CHE.

Regarding sediment flow, the mobilization threshold was considered similar in the two gauges. The conditions of slope, cross-section and average size of the sediment are very similar, setting it at 400 $m^3 s^{-1}$ for the entire series 1950-2019.

For the second stage, the collection of the different river management actions was carried out following a double procedure. On the one hand, from personal interviews with those responsible for its execution and from documentation provided by these people, which was verified with data from the archive and communication notes from CHE. On the other hand, we worked with the most recent orthophoto (2018) from Geographic Information and Spatial Data Infrastructure of La Rioja (IDERioja), Navarra (IDENA) and Aragón (IDEAragón).

The location of the actions carried out in the Ebro River channel was mapped with the ArcGIS 10.5 software. The information was stored in a Geodatabase with three Feature classes of polygonal, linear and point geometry. This triple geometry gathers all the variability of performances. Polygonal geometry was used for the following 7 types of actions: bridge and road permeabilization, controlled flooding area, “curage”, obstacle removal, relief channel, redistribution, and setback (space) –dike removal–. Lines were used for the dike removal and dike lowering performances, whereas the point only for the gate in security perimeter. The compilation, location, classification and representation of all the river management actions, as well as the identification of those already carried out and those that are in progress, has been a complex task, due to the lack of an official registry and the diversity of sources that were necessary to inquire, as already indicated.

3. Results

3.1. Re-characterization and changes in the Ebro floods

The modification of peak flow data made by CHE for the values of the new series (from the 1996-97 hydrological year and ongoing), can be seen in the changes registered for the maximum flow of each year (Table 1). In Castejón, the annual maximum instantaneous (Qci) flows have experienced increases and decreases in equal parts, while in Zaragoza the values decreased in most of the years. On average, the magnitude of the changes has meant an increase in Castejón (+4.53%), with specific decreases of 100 $m^3 s^{-1}$ in the Qci for the 1997-98 year, compared to a decrease in Zaragoza (-3.13%) with reductions of up to 595 $m^3 s^{-1}$ in the flood of February 2003. In this sense, the revised data confirm a greater lowering of the peak flood between Castejón and Zaragoza, especially relevant in floods such as those of February 2003 and April 2007, with laminations of 559 $m^3 s^{-1}$ and 468 $m^3 s^{-1}$, respectively.

Table 1. Annual maximum instantaneous flow (m^3 s^{-1}) in the old official series and in the new modified series at the gauging stations of Castejón and Zaragoza. Marked in red are the modifications in which the flow has been increased, in green those that have been decreased and in yellow those that have maintained the same value. In the flow lowering column the negative cases indicate that the flow rate has not been lowered, but that instead has increased between Castejón and Zaragoza.

year	Castejón (9002)		Zaragoza (9011)		flow lowering Castejón-Zaragoza	
	old	new	old	new	old	new
1996-97	2380	2380	2004	2012	376	368
1997-98	1475	1372	1469	1488	6	–116
1998-99	791	791	845	828	–54	–37
1999-00	737	737	769	745	–32	–8
2000-01	1666	1566	1575	1488	91	78
2001-02	592	592	579	571	13	21
2002-03	2883	2847	2832	2237	51	610
2003-04	1113	1111	1145	1115	–32	–4
2004-05	774	770	793	768	–19	2
2005-06	1575	1604	1472	1412	103	192
2006-07	2144	2282	2282	1952	–138	330
2007-08	1710	1797	1567	1498	143	299
2008-09	1736	1797	1619	1604	117	193
2009-10	1935	2054	1572	1549	363	495
2010-11	1176	1164	1003	998	173	166
2011-12	676	740	623	623	53	117
2012-13	2146	2203	1755	1755	391	448
2013-14	1612	1527	1554	1554	58	–27
2014-15	2691	2691	2448	2448	243	243
2015-16	-	1490	-	1357	-	133
2016-17	-	1606	-	1236	-	370
2017-18	-	2682	-	2037	-	645
2018-19	-	1911	-	1458	-	453
mean value	1569	1640	1469	1423	100	217

Therefore, for the analysis it is necessary to cut the available series and work separately on what happened before and after 1996. Figure 2 shows, first, how the maximum flow rates of each year were higher in Castejón and in Zaragoza in the old series 1950-1996 (henceforth series 1) than in the new series 1996-2019 (henceforth series 2). Second, there has been a decreasing trend in the old series, while in the last 23 years (series 2) the maximum flow rates of the floods have tended to increase.

Table 2 shows a detailed analysis of all the floods registered above the bankfull threshold between 1950-2019 in Castejón and Zaragoza. The values show a marked difference in the flows between series 1 and series 2. The most significant fact is that in series 1 there are 46 episodes (i.e 1 per year on average), while in series 2, 15 are recorded (i.e. average of 0.625 per year). This trend, differentiated by series, also occurs in peak flows, 92 in series 1 (i.e. 2 per year and 2 per episode) and 32 in series 2 (1.39 per year and 2.13 per episode), as well as in the days over the movement threshold (e.g. Zaragoza: average 28 and 29 days over the movement threshold per event in series 1 and 2 respectively, while the average number of days per year over that threshold is 28 and 19, respectively). Therefore, it can be pointed out that series 2 is characterized by less floods and less peak flows, but slightly longer and more complex than series 1. By gauging station, Zaragoza presents more total volume, more bankfull days and more episodes over sediment flow mobilization threshold than in Castejón.

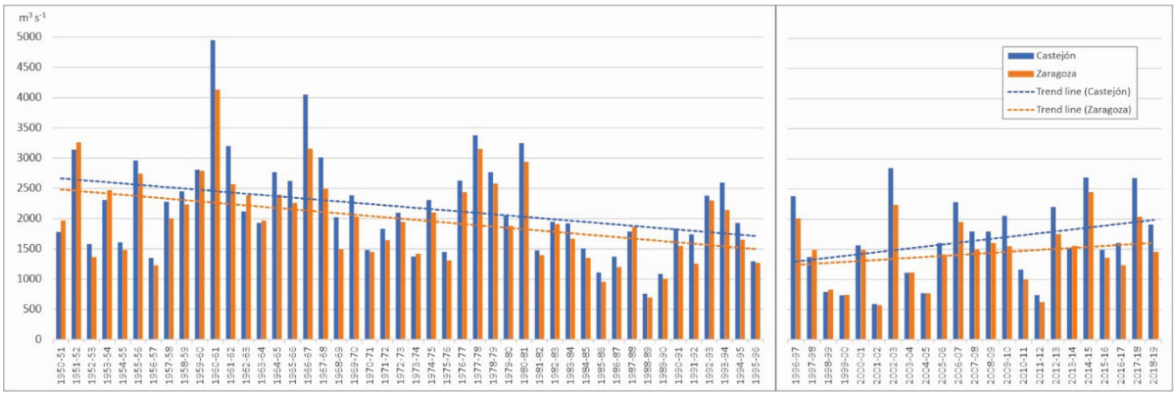

Figure 2. Annual maximum instantaneous flows ($m^3\ s^{-1}$) and trend lines in the old official series (series 1, until 1996) and in the modified one (series 2, since 1996) of the gauging of Castejón and Zaragoza.

Table 2. Data of all the floods registered above the bankfull threshold in Castejón and Zaragoza gauging stations since 1950. Those corresponding to series 2 (1996-2019) are shaded in gray.

			Castejón				Zaragoza			
year	month	num. of peak flows	Qci $m^3\ s^{-1}$	total volume hm^3	days > sediment mobilization threshold	days > bankfull flow	Qci $m^3\ s^{-1}$	total volume hm^3	days > sediment mobilization threshold	days > bankfull flow
1951	03	3	1780	2710	35	0	1971	3032	40	2
1952	02	1	3140	1040	9	3	3260	1142	11	3
1952	04	1	2390	1374	23	1	1975	1231	19	1
1953	10	1	2270	442	4	1	2000	542	6	1
1954	01	1	1925	579	8	1	1780	841	12	1
1954	02-03	2	2310	3443	43	6	2470	3994	47	9
1956	05	1	2960	701	9	1	2744	858	10	2
1958	03	1	2280	1817	26	2	2003	1648	24	3
1958	12	2	2450	1194	14	2	2237	1170	14	2
1959	12	3	2810	4498	43	6	2790	4557	44	11
1960	01-02-03	3	2220	4847	78	5	2324	4625	85	6
1960	10	1	2040	536	7	1	1830	729	12	1
1960-61	12-01-02	2	4950	7379	80	9	4130	7219	79	13
1961	11-12	3	3200	3112	34	4	2570	3310	36	8
1962	01-02-03	7	1850	5038	76	2	1850	5255	76	3
1962	12	1	2120	783	9	1	2390	788	8	2
1963	03-04	1	1365	937	15	0	1620	1022	15	1
1963	12	1	1930	599	9	1	1970	798	11	1
1964	12	1	1700	521	6	0	1695	550	6	1
1965	01	1	2771	917	10	1	2395	963	10	2
1965	12	2	2622	2695	39	2	2260	2114	31	2
1966	02-03	2	1850	2192	31	1	1611	2109	31	1
1966	11-12	4	4050	4107	47	4	3154	4009	47	5
1967	11	1	2082	464	5	1	1980	567	6	2
1967-68	12-01	4	3012	3087	33	5	2494	2864	33	5
1969	03	1	2024	1284	15	1	1453	1083	16	0
1969	04	1	2024	1353	18	1	1495	1156	18	0
1969-70	12-01	4	2388	3595	51	3	2031	4596	65	6
1972	02	4	1832	2836	44	1	1644	2996	54	1
1973	02	1	2097	1068	13	1	1946	1142	15	2
1975	04	2	2309	2197	36	1	2100	2121	35	1
1977	06	1	2628	793	9	2	2437	803	9	2
1978	01-02-03-04-05	7	3375	9373	125	10	3154	8638	117	11
1979	01-02	3	2770	4080	46	4	2581	3883	46	7
1979	11	1	2056	820	10	1	1880	853	9	2
1980	05	1	1912	411	6	1	1804	390	6	1
1980	12	1	3250	1280	15	2	2908	1434	17	3
1981	01	2	2674	1540	14	3	2940	1690	15	5
1982	12	3	1950	1921	21	1	1910	1939	22	2
1984	05	1	1921	897	13	1	1668	974	15	1
1988	04	3	1788	2214	34	0	1869	2513	35	2
1991	05	2	1837	1402	20	1	1427	1419	21	0
1992	10	1	1990	361	4	1	1541	360	5	0
1992	12	1	2380	1105	15	2	2301	1191	14	2

			Castejón				Zaragoza			
year	month	num. of peak flows	Qci $m^3 s^{-1}$	total volume hm^3	days > sediment mobilization threshold	days > bankfull flow	Qci $m^3 s^{-1}$	total volume hm^3	days > sediment mobilization threshold	days > bankfull flow
1993	12	1	2595	1617	21	2	2140	1679	26	3
1995	03	1	1930	859	13	1	1652	793	12	1
1996	12	3	1769	1978	31	1	1443	2236	38	0
1997	01	1	2380	1533	22	1	2012	1779	26	3
2002	12	1	1887	841	11	1	1574	923	12	1
2003	02	1	2847	1549	19	2	2237	1903	23	5
2003	03	2	1489	1001	15	0	1806	1368	16	2
2007	04	3	2282	2193	27	1	1952	2501	30	4
2008	06	2	1797	1362	21	1	1498	1503	24	0
2009	02	2	1797	2012	27	1	1604	2154	28	1
2010	01	1	2054	629	7	1	1549	629	9	1
2013	01-02-03-04	6	2203	7123	93	2	1755	7500	93	4
2013	06	2	1853	902	14	1	1428	808	13	0
2014	03	1	1612	902	11	0	1554	945	12	1
2015	02-03-04	4	2691	5411	63	5	2448	5623	67	11
2018	04	1	2682	1862	24	2	2037	2005	24	5
2019	01	2	1911	1569	21	1	1458	1491	22	0
total and mean 1950-1996		92	2387	2087	1236	100	2182	2122	1285	140
total and mean 1996-2019		32	2084	2058	406	20	1757	2225	437	38
total and mean 1950-2019		124	2312	2080	1642	120	2078	2147	1722	178

The update of the flood data in the last 23 years also implies the modification of the return periods (Table 3 and Fig. 3). Considering the total series 1950-2019, in Castejón there is no change in the values when updating the data, while in Zaragoza there is a slight decrease. The behavior by series (1 and 2) reflects a notable decrease in flows in all return periods for both stations, with a downward gradient in the percentage difference from smallest to largest magnitude. In Castejón the decreases range between 29% (Q2) and 17% (Q500), while in Zaragoza between 27% (Q2) and 14% (Q500).

Table 3. Flow rates ($m^3 s^{-1}$) for different return periods (t) obtained from the Gumbel adjustment at Castejón and Zaragoza gauging stations for the total series 1950-2019, for series 1 (1950-1996) and for series 2 (1996-2019).

		2 years	5 years	10 years	25 years	50 years	75 years	100 years	500 years
Castejón	1950-2019 with old data	1875	2647	3159	3805	4284	4563	4760	5860
	1950-2019 with new data	1878	2651	3163	3809	4289	4568	4765	5866
	1950-1996 (series 1)	2062	2860	3389	4056	4551	4839	5043	6179
	1996-2019 (series 2)	1474	2187	2660	3257	3699	3957	4139	5154
Zaragoza	1950-2019 with old data	1707	2381	2827	3391	3809	4052	4224	5184
	1950-2019 with new data	1690	2357	2798	3356	3769	4010	4180	5129
	1950-1996 (series 1)	1880	2570	3028	3605	4034	4283	4460	5443
	1996-2019 (series 2)	1372	2012	2436	2972	3369	3600	3763	4675

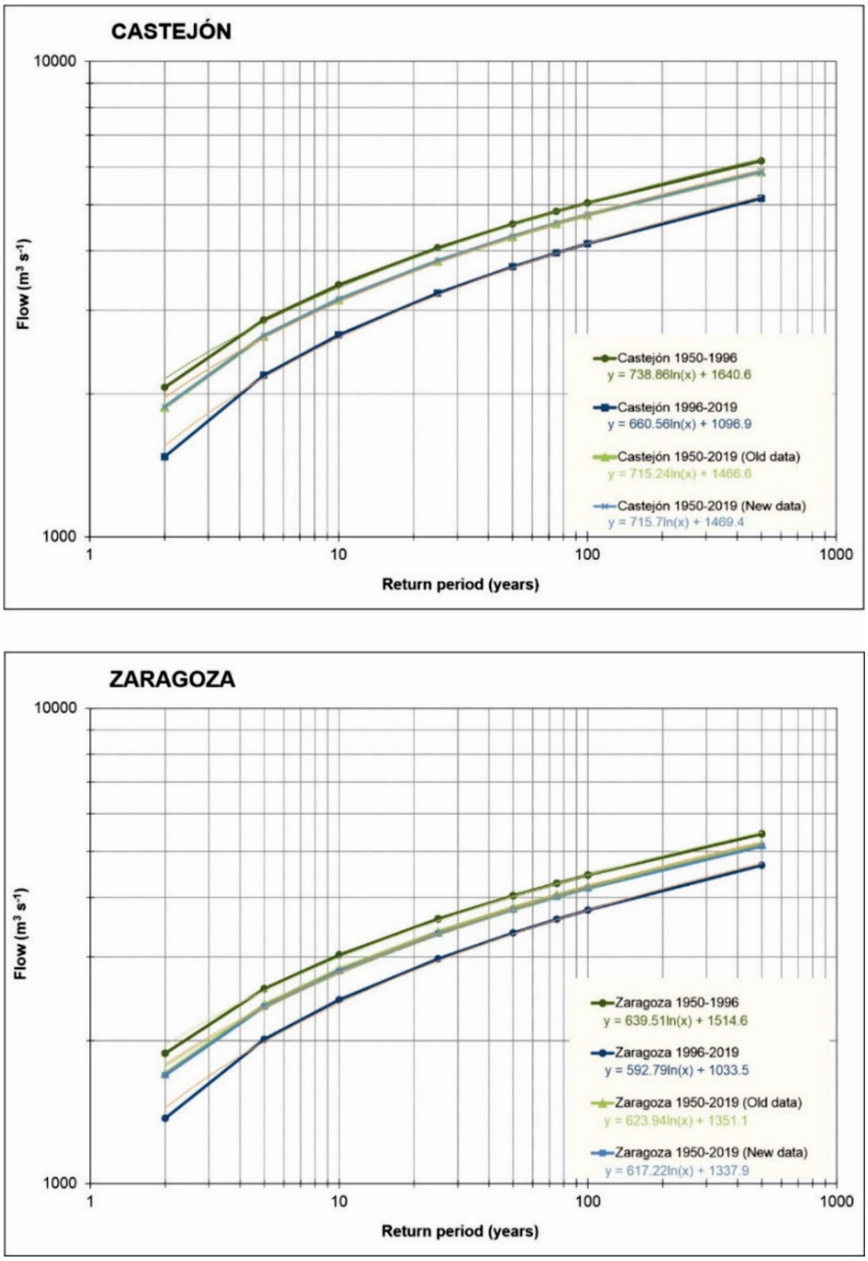

Figure 3. Equations and curves to determine the return periods.

The importance of the lack of confidence in old data is quite remarkable; as an example, the flood that marks the peak value of the series, with 4950 $m^3 s^{-1}$ in Castejón on December 31, 1960. According to series 1, its return period would be ~90 years. If we apply the new return periods corresponding to series 2, in which it is assumed that the flood flow is already correctly measured, the peak flow of that flood in Castejón would have been 4056 $m^3 s^{-1}$, that is, 894 $m^3 s^{-1}$ less than the measured value. In the case of the Zaragoza gauging station, a peak flow of 4130 $m^3 s^{-1}$ was recorded on that event on January 2, 1961. According to series 1, this value represented a return period of ~60 years. For this return period, series 2 indicates a peak flow of 3458 $m^3 s^{-1}$, that is, 672 $m^3 s^{-1}$ less than what was measured. These new values, “corrected” in a very simple way, of 4056 $m^3 s^{-1}$ in Castejón and 3458 $m^3 s^{-1}$ in Zaragoza, are much more consistent with the levels reached (not only with the officials of the gauging stations, but also with those of the existing markers in some settlements) and with the flood lowering level, both for the authors of this article and for the technical personnel of CHE.

The seasonality of the floods is not a function of the quality of their measurement, so it is a parameter that can be analyzed in the whole of the 1950-2019 series for all recorded events, i.e. those that exceeded the bankfull flow in Castejón and/or in Zaragoza. However, as seen in Figure 4, series 2 floods are concentrated in winter and spring, with the same number of events in January, February, March and April, whereas those of the autumn season (October, November and early December) that happened in series 1 are completely disappeared. This phenomenon must be related to regulation, since the reservoirs have the capacity to retain the first floods that occur after the summer dry season.

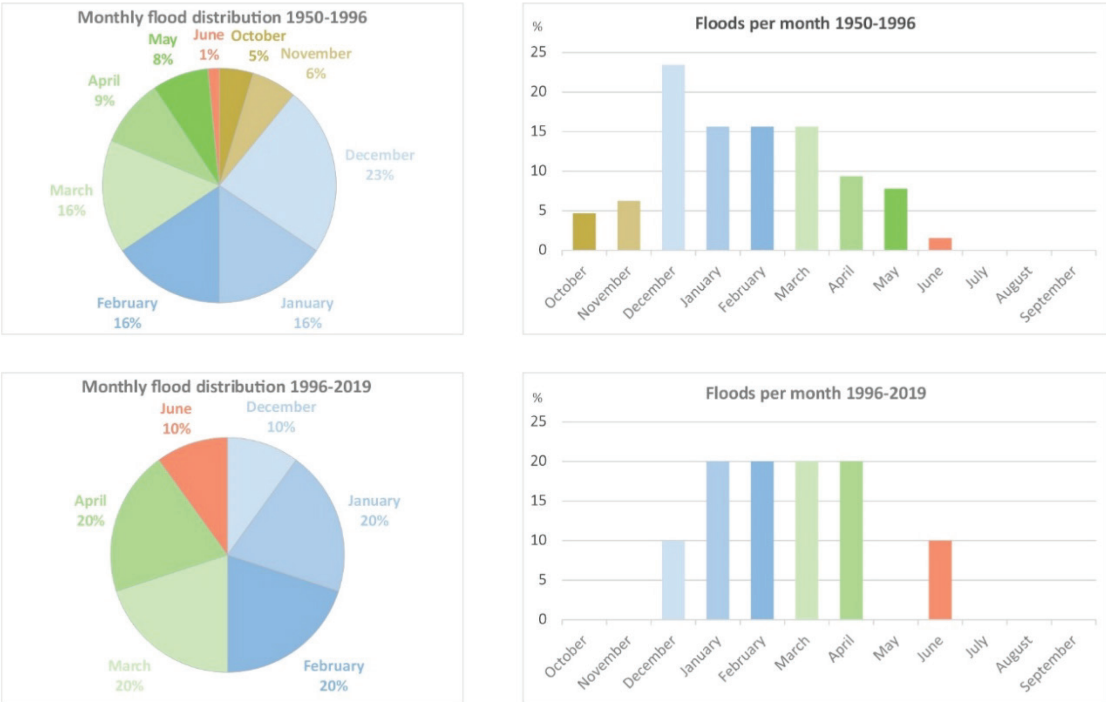

Figure 4. Monthly flood event percentage.

Another issue that can be analyzed in its evolution throughout the entire 1950-2019 series is the simple or complex nature of the events and the shape of the hydrographs (Fig. 5). A trend towards increasing, more complex floods over time seems clear, with several points (2 per episode in series 1 and 2.13 per episode in series 2, as already noted), and slower, with flattened hydrographs, as already found by Sánchez Fabre *et al.* (2015). To a large extent it seems to be due to the regulation of flows, to the increasing use of reservoirs for control and peak flow lowering in each flood. And this could lead to a new hypothesis: that the current floods are more voluminous than the old ones (about 100 hm^3 in Zaragoza, however, in Castejón the average volume is 30 hm^3 less), but their peaks are being lowered by the reservoirs. Therefore, regulation is affecting both seasonality and maximum flow values.

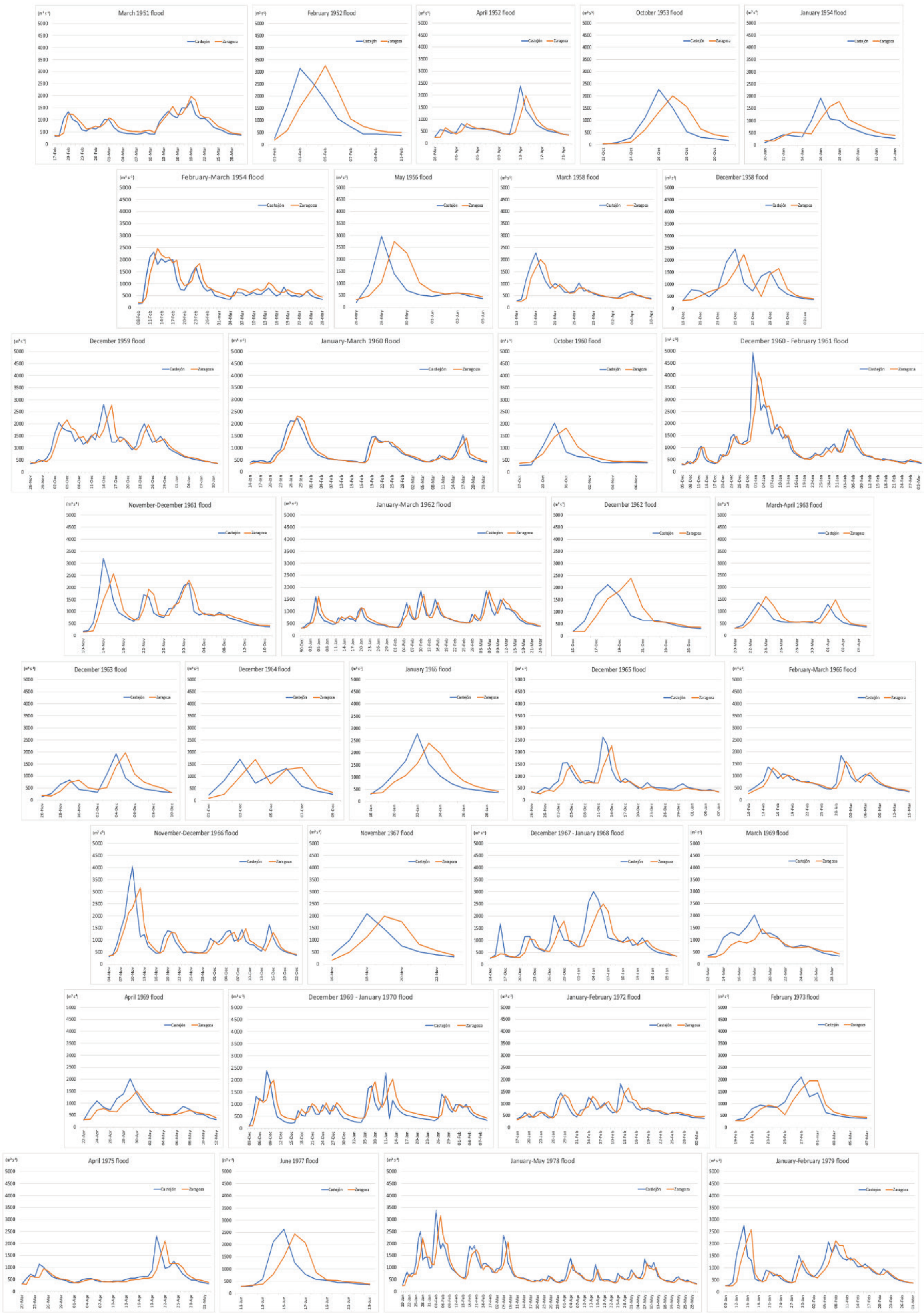

Figure 5. Hydrographs of floods since 1950.

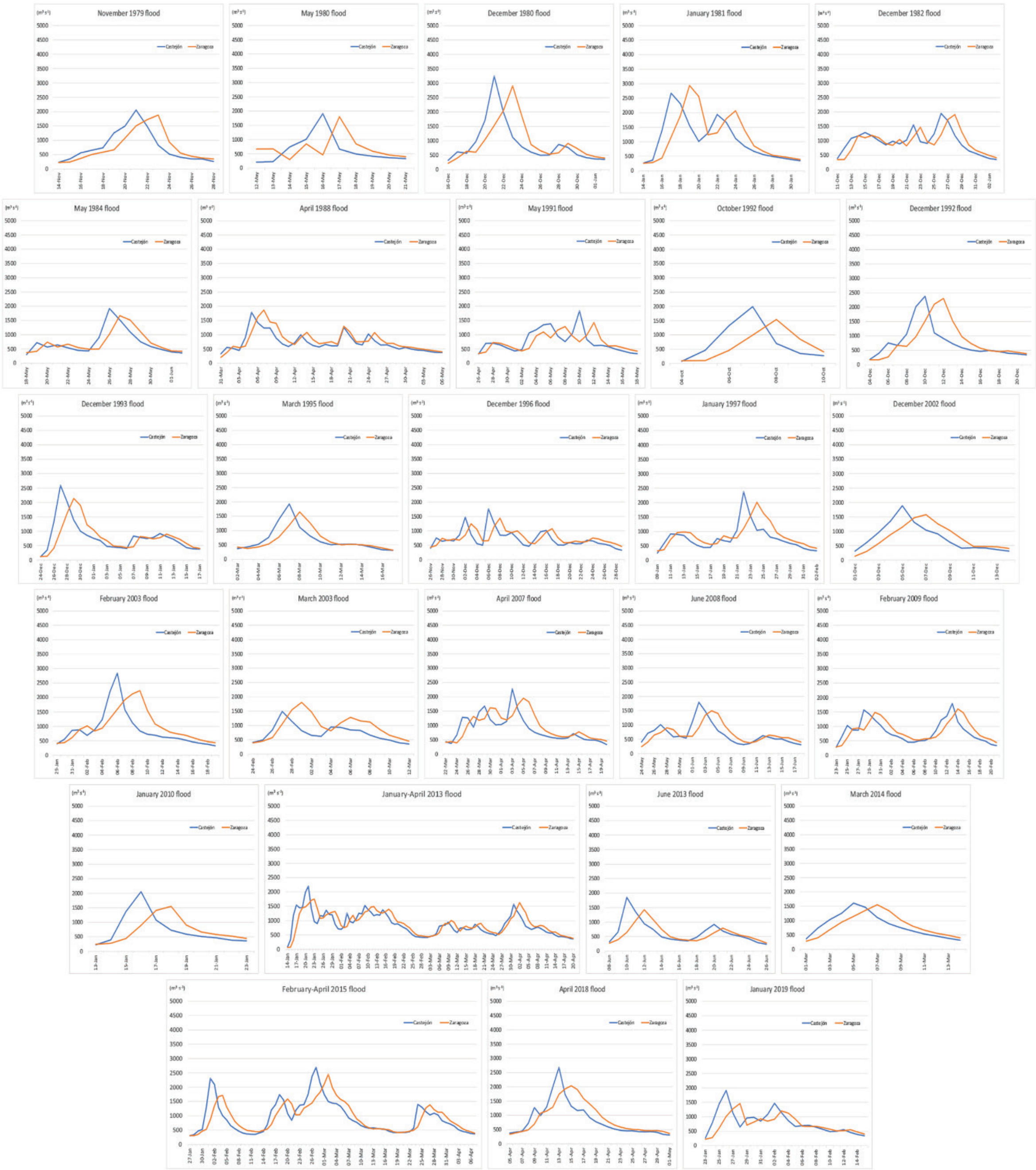

Figure 5. Hydrographs of floods since 1950 (cont.)

Figure 6 shows with second degree polynomial curves that the descending trends of maximum flows in Castejón and Zaragoza stop, approximately, from 1996, coinciding with the new period of corrected data (series 2). From this year there is a marked trend towards stability. In the case of the Mendavia gauging station, the line remains approximately horizontal throughout the entire period of time. The rest of the gauging stations maintain the same behavior as the nearby stations. This first analysis of the data seems to confirm the hypothesis, already alerted to by the Hydrology and Channels Area of CHE, that flood flows historically presented calculation deficiencies, at least until 1996, and that in general before that date, the maximum flows registered in the gauging stations of Castejón and Zaragoza were overvalued. The problem is that it is impossible to reconstruct the flood flows prior to 1996, so the evolutionary interpretation is still hypothetical. Historic floods, prior to 1950, cannot help either because of the unreliability of the data. To all this is added the scarcity of marks and records on the ground for the different floods. Ancient floods have been studied in as much detail as possible, the vast majority of events are well-known, and their peak flows have been estimated from models (Balasch *et al.,* 2019), but the calculated flows cannot be integrated into the analysis with current ones due to temporary gaps and methodological differences. In any case, it does seem evident that there were great floods in the past with values much higher than those of the last century: Balasch *et al.* (2019) have calculated 5560 m^3 s^{-1} for that of 1643, 5180 m^3 s^{-1} for that of 1775, 4600 m^3 s^{-1} for that of 1787, 4844 m^3 s^{-1} for that of 1871 and 3600 m^3 s^{-1} for that of 1930.

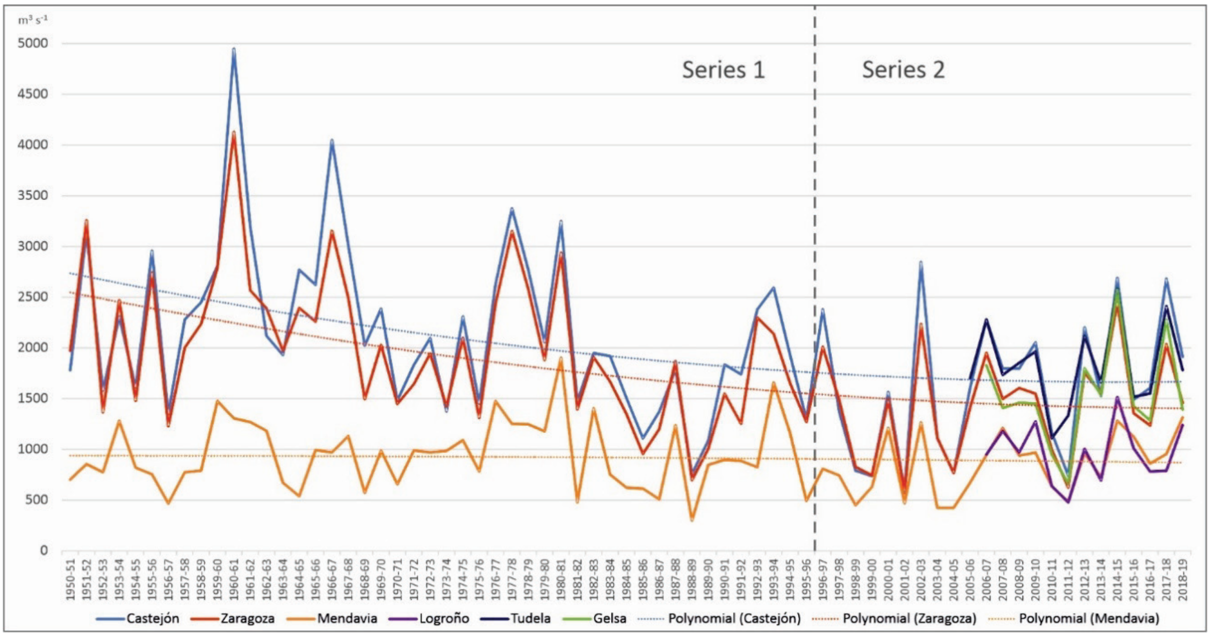

Figure 6. Evolution of annual peak flows (m^3 s^{-1}) in the 6 gauging stations of the Middle Ebro River and second-degree polynomial curves trend lines of the 3 gauging stations with complete series.

Figure 7 shows the evolution of the annual mean data adjusted with a third-degree polynomial line. A marked wet period is observed from 1950 to 1988, the driest during the last decade of the 20th century and first decade of the 21st century, and the new increase in flow rates in the second decade of the 21st century. Also highlighted is the fact, reflected in the trend lines, that in most of the years up to 1979 a higher average flow was recorded in Castejón than in Zaragoza, whereas from that date the opposite is clearly the case. This may be due to different factors, for example, variations in water consumption for agriculture (Imperial and Tauste Channels) or contributions from the tributaries (Queiles, Huecha, Arba and Jalón Rivers) that arrive between the two gauging stations. But it can also confirm that i) the flows before 1996 were not well measured, or ii) the flood flows were frequently overvalued, with the consequent repercussion on the computation of the annual average flows. Inverse behavior to that of the annual peak flows, which maintains throughout the series from 1950 to 2019, higher values in Castejón than in Zaragoza, linked to the lowering of the peak of the flood that the overflow allows.

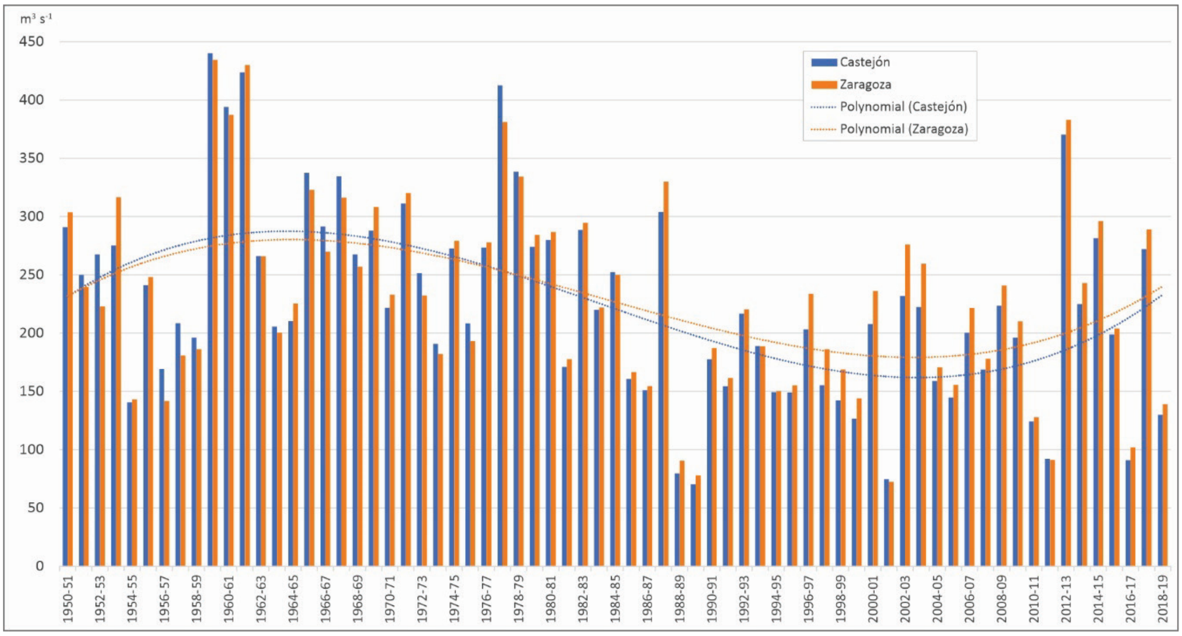

Figure 7. Evolution of annual average flows (m^3 s^{-1}) since 1950 and third-degree polynomial trend lines in the gauge stations of Castejón and Zaragoza.

3.2. Management risk evolution

The floodplain in the Middle Ebro River constitutes a risk territory with a total area of 744 km^2. Throughout history, this area of enormous fertility has been used for agricultural purposes. Most of the towns are located outside its limits, sheltered from the flood, but some also are located within the floodplain, at strategic points. Traditionally, floods caused damage, but economic and social activity was respectful and adapted and kept there because the benefits were greater (Ollero, 1992). The Middle Ebro River has two key characteristics from a danger point of view: flooding and bank erosion. Flooding is high, since floods with return periods of 10 years occupy 80% of the surface of the floodplain (Ollero, 2010). Bank erosion is very active, as demonstrated by a long history of continuous migration and meandering, as well as avulsions and river style changes between meandering and wandering both in space and in time (Ollero *et al*., 2017).

Risk management is therefore made up of measures to reduce damage from flooding and erosion, and has evolved throughout history. Four phases can be identified (Fig. 8):

Initial Phase. Approximately until 1945, without flow regulation and with very few bank protection actions. These began around 1900 and were local, in specific meanders to avoid erosion and with very precarious means. The Ebro River reservoir, built in the headwaters in early 1945, marks the beginning of the regulation.

Maximum intervention phase against the river (1945-1990). It clearly marks, in the context of the Middle Ebro River, the introduction of the “Anthropocene”. Regulation is extended with reservoirs, highlighting that of Yesa (1960), and a large number of bank defense works and kilometers of dikes are constructed after the great floods of 1959 and 1960-61. As a result of these works, the fear to the river is lost and the crops are moved towards the banks, gradually reducing the river space (Horacio *et al.,* 2019) and increasing the exposure to risk. A new period of floods (June 1977, winter-spring of 1978, December 1980 and January 1981) generates significant damage and a new wave of defense actions takes place that complete the dikes, avoiding totally the dynamics of any meander (Ollero, 1992; Najes *et al.,* 2019), considerably simplifying the channel (Ollero *et al.,* 2015). With all this, a defense system has been created that destroys the fluvial dynamics, but it is ineffective and requires continuous maintenance, although the scarcity of floods between 1981 and 2003 seems to consolidate it and gives security to the riverside population, completing the vicious circle by increasing once more the agricultural and urban exposure in a flood zone (Ollero *et al.,* 2017).

Scientific awareness phase (1990-2015). Throughout this period, the scientific community is alerted to the fragility of the management system and the destruction of the Ebro River is denounced as a dynamic meandering system, unique for its dimensions on the Iberian Peninsula. This concern is not taken seriously in society, but little by little it convinces the technical field, especially since the enactment of 2000/60/EC Directive, the preparation of the Ebro River Environmental Plan in 2005 and even more so, after the approval of 2007/60/EC Directive. However, in political decision-making, the traditional defense system still continues to be maintained and consolidated.

Current phase of shift (2015-2020). It begins with the flood of 2015 and settles with that of 2018, in which the technicians of CHE put their criteria into practice, originating from scientific awareness (until then it had not been taken into account). In this phase, the European demand of FRMPs is key, in its first preparation for 2015 and in its current second cycle until 2021. However, this moment of change has intense social opposition in the riverside towns, a belligerent standpoint by associations of "those affected by floods" that do not welcome the new management measures and intend to continue with the traditional defense system. In the process of participating in the new Ebro River Resilience strategy, this controversy is revealed. But this strategy is already a new way of acting, is proposed in the mid-term and can constitute a paradigm shift without turning back.

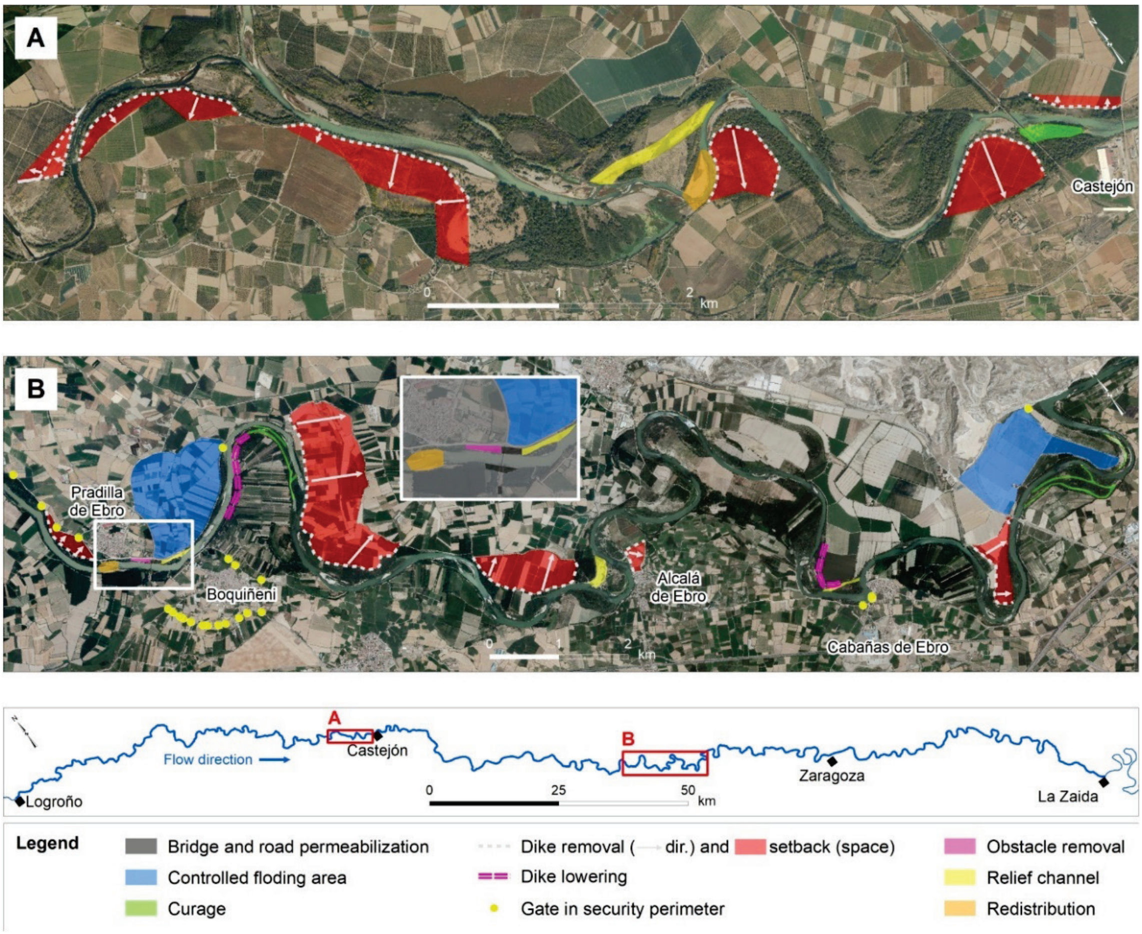

Figure 8. Actions implemented in the Alfaro-Castejón (A) and Pradilla-Cabañas (B) sectors.

Ebro River Resilience strategy emerged in 2018 led by the competent Ministry through the CHE. The autonomous governments of La Rioja, Navarra and Aragón also participate, along with local entities in seeking the consensus of those affected people, associations and the university community. Its objective is to search for new approaches to deal with a complex problem and an inevitable natural phenomenon: prevention, protection, preparation and repair as measures to reduce the risk of flooding in the Middle Ebro River, and always in the context of the Ebro's FRMP (Gargantilla *et al.,* 2020).

The strategy includes predictive measures, such as the improvement in the collection of hydrological data and the correction of flows that we have already analyzed, as well as educational, informative and social involvement. But the most notable are the actions that try to consolidate a new prevention and defense system based on giving more space to the river. It should be noted that the latest amendment to the Regulation of the Public Hydraulic Domain (December 2016) states that as far as possible it will tend to "increase the space (width) of the channel and not aggravate flooding and pre-existing risk". In addition, it indicates that laterally to the channel raised defense works may only be built in the area of preferential flow or floodway "when they protect existing populations and public infrastructures".

The measurements carried out until May 2020 have been compiled, quantified (Table 4) and mapped (Fig. 8). Altogether they add up to 120 actions, with the removal of more than 26 km of linear elements and the achievement of 2,084 ha of free surface for flowing (138 ha) and for flooding (1946 ha). They respond to the following typology:

- *Elimination and setback of dikes.* They are longitudinal levees of compacted soil. So far, 18 cases have been acted on, reaching a total of more than 23 linear km. The objective of their elimination is to achieve greater river space, a total of 595 ha so far, favoring overflow and reducing energy in the floodway. In most cases, a setback has been carried out, that is, the removed dike has been replaced by reinforcement as a defense for a pre-existing internal path.
- *Lowering of dikes.* In 4 cases so far, 3.1 linear km in total, this action has been chosen, which favors, to a lesser extent, the mitigation of water pressure in floods. On average, it means reducing the height of the dike from ~3 m to ~1.5 m. It is associated with the location of floodgates and aims a controlled flooding above a level close to that of bankfull flow.
- *Temporary controlled flood areas.* 9 flood areas have been established so far, with a total floodable area of 1351 ha. They are associated with settlements and have a gate that connects them to the channel for filling and emptying functions. This floodgate is always located downstream of the area, so that it is flooded from its lower level, at the opposite end, in a progressive way without causing damage to the terrain. The first to be executed was that of Pradilla and, along with other associated actions, it had an excellent performance for the village in the 2018 flood.
- *Relief channels.* Also associated with the mitigation of damage in the vicinity of settlements. They were the first projected measures, more than a decade ago, but they were highly discussed and there were no possibilities of execution until 2015. 6 have definitely been carried out, but it is likely that they will not be carried out any more since it seems more popular to technically chose for the so-called "curages".
- *"Curages".* They consist in large masses of vegetated sediments permeabilised by opening branches of free circulation of flow. It increases the drainage capacity temporarily, until the river dynamics and vegetal development themselves close those branches again and requires a new intervention. Between 2018 and 2020 it was the most implemented action, with a total of 35 actions. There are more implementation projects for the coming years.
- *Sediment redistribution.* In 5 cases, sediment mobilization procedures have been carried out with machinery within the active channel, extracting it in one part of its section and

accumulating in another. They seek to create a greater capacity for temporary drainage and to modify the flows to avoid the direction of the current against a settlement (e.g. the case of Pradilla).

- *Security perimeters.* They are a control system for overflowing waters for settlement protection. 12 have been implemented so far. Existing infrastructures (roads, highways, walls, among others) that are leveled or increased their height are used to build a security cordon that surrounds the urban area. The implementation of closing elements and gates along the perimeter is necessary, as well as markers to follow the evolution of the levels in situ and establish height/time correlations that help with decision-making (for example, in the case of an evacuation).
- *Permeabilization and removal of obstacles*. They are specific actions that allow drainage capacity in key places such as bridges and close to settlements. The actions carried out in the area of the Boquiñeni-Pradilla bridge or those of Pina and Novillas stand out, as well as the removal of the building of the old canoeing club in the latter village.

Table 4. Number and dimensions of implemented actions.

measures	actions	lineal km	free area (ha)
Dike removal and setback	18	23.46	594.57
Dike lowering	4	3.1	
Controlled flooding area	9		1,351
Relief channel	6		28.21
“Curage”	35		87.16
Sediment redistribution	5		23.39
Gate in security perimeter	30		
Permeabilization and obstacle removal	13		
Total	120	26.56	2084.33

4. Discussion

In the context of the Ebro River Basin and its main course, a process of notable population, territorial, environmental and technological changes was witnessed in the central decades of the 20th century, which has been analyzed from very different perspectives and in different scenarios (e.g. Beguería *et al.,* 2003; Batalla *et al.,* 2004; Domenech *et al.,* 2008; Cabezas *et al.,* 2009; García Ruiz and Lana-Renault, 2011; Lorenzo *et al.,* 2012; García Vera, 2013; López Moreno *et al.,* 2011, 2014; García Ruiz *et al.,* 2011, 2015; Ollero *et al.,* 2015, 2017; Sánchez Fabre *et al.,* 2017). In these referenced works, these changes began to be reservedly associated with the global context of consolidation of the “Anthropocene”. In this article we consider that there is sufficient evidence to affirm this association. The changes observed in the basin, hydrology and the Ebro River channel are the confirmation of this new period in our environmental history. Fluvial functioning is an excellent indicator for this (Ollero, 2011).

“Anthropocene” is a term used to define human influence on Earth and its evidence in the geological record, although still without official validation and not without some controversy at its beginning, lack of geological record or relevance. The commission in charge of its definition has established a start date of 1945 (Waters *et al.* 2016). The 1950 milestone can be seen as the beginning of the “big acceleration” (Steffen *et al.,* 2004) expressed by the Anthropocene Working Group since 2009 (Zalasiewicz *et al.,* 2017).

However, the origin of the term, and even more so the concept, is much earlier. Rull (2018) makes an analysis and compilation on the state of the matter. Not surprisingly, as early as 1873, Antonio Stoppani, in his definition of the “Anthropozoic”, exemplified how engineering works have modified natural waterways and reduced or eliminated overflows, thereby altering the hydro-sedimentary operation. Others point out that the anthropic influence on natural systems is precisely what differentiates the Pleistocene from the Holocene, and that events such as changes in land use with the appearance of agriculture have already led to changes (Constante *et al.,* 2010). Thus, the formation of the Ebro Delta has undergone an important development since Roman times linked to the modification of land uses in the basin and the increase in sedimentary contribution, a process in recession derived from a new reforestation and the construction of reservoirs (Maldonado, 1972; Guillén and Palanques, 1997). This does not prevent us from indicating that the course of the Ebro River has undergone an alteration in its operation in an accelerated way throughout the 20th century, and especially from the middle of it with the construction of reservoirs and the defense of the banks and constriction of its channel.

In the evolution of the “Anthropocene” in the Middle Ebro River up to the present time, we have identified three phases: that of maximum intervention (1945-1990), that of scientific awareness (1990-2015) and that of the current paradigm shift (2015-2020). It is necessary to highlight some Ebro River floods that have been key in this evolution (Fig. 9).

- That of 1960-61, the largest in the 20th century, marked the beginning of general defense actions.
- Frequent events between 1978 and 1981 caused the defense system to be completed and with it the final stabilization of the channel.
- The absence of extraordinary floods between 1981 and 2003 generated the dichotomy between two opposing perceptions: scientific awareness of the problem and the need for environmental measures in the face of the false sense of safety and the confidence of riverside society in enforced reservoir regulation mechanisms and defense.
- The flood of 2003 reactivated social concern but showed a general absence of historical memory: references had been lost. The Ebro River Environmental Plan is promoted, where the scientific field expresses its ideas, but it is not executed.
- The floods of 2007 and 2008 coincide with the start-up of the Zaragoza 2008 International Exposition, focusing concerning in urban areas (Pueyo *et al.,* 2017). Specific initiatives to flood rural areas upstream to save the Expo were implemented, but no progress in implementing new management ideas was given, except at a scientific level.
- Once again, the floods of 2013 and 2015 broke social patterns and associations of affected people against the river authorities rewoke with great virulence, trying to avoid the start of the paradigm shift that is already evident.
- The 2018 flood definitively consolidates the decision of Ebro River Authority to change the paradigm and shows again the disagreement of those affected.

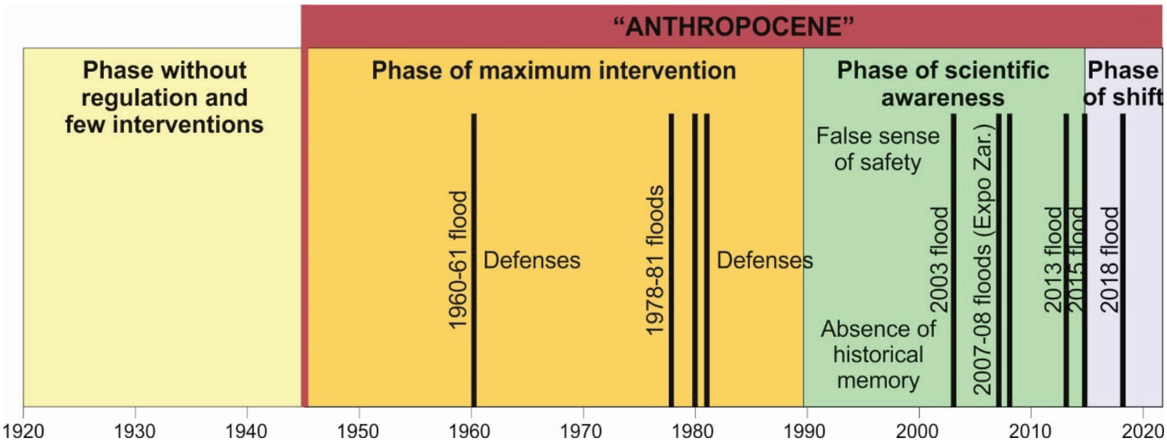

Figure 9. Evolution of risk management and perception in the last century and main floods in the last 70 years.

In this context of change, it is necessary to periodically establish moments of scientific and technical reflection and evaluation, objectives that the present work pursues. This evaluation and monitoring are important for risk management that must always be adaptive, modifying it based on the changes observed and the results obtained in previous phases, marking a permanent learning process of the river's behavior (Klijn *et al.,* 2015). In this sense, the current change has been advocated based on the failures detected in the previous management systems. But there is another very relevant aspect: it is essential to well know the floods and to have reliable hydrological data, as measures can be built on that basis, can be properly evaluated and, in short, decisions can be taken. Hence the importance of old maximum flows having been revised and that in these new flows we can reflect and better understand the hydrological functioning of the Middle Ebro River.

It is evident, and recognized by those in charge of data collection, that the quality of the Ebro River flow records in a flood presented significant deficiencies and error margins that have only been partially corrected (and since 1996). Therefore, a longer series from that year is necessary to achieve a better knowledge of the Ebro River floods, but, for the moment, a first necessary action was, based on the corrected data, the re-characterization that has been done in this study.

Systematic hydrological measurement in floods still has limitations. The margins of error have not been evaluated at a scientific level: it is modeled for channels without gauging stations, but the data recorded in conventional stations are generally considered to be good. But it seems that the margins of error were remarkable in the past and are decreasing with new techniques. A river of the Ebro's relevance as a great peninsular river, with numerous gauging stations and very long record series, should be a model for data collection. For this reason, the present revision and others that could be carried out in the future should be published, as well as carrying out similar revisions in other river courses.

On the other hand, we are still far from being able to state to what extent the hydrological changes observed in the last 70 years are due to natural or anthropogenic factors, global change or the effects of flow management, and to what extent they are responsible for hydrogeomorphological changes in the channel. The present investigation advances along these lines, but it is a first approximation and cannot reach definitive conclusions. There is a need for a more robust procedure that we will have to implement in future work.

As already indicated, these progressive advances in hydrological knowledge should be taken into account in the adaptive management of flood and erosion risks (Woodward *et al.,* 2014), a management whose objective must be social resilience (effective measures) and also ecological (adequate and sustainable measures). First, prediction and emergence are critical and improve as hydrological knowledge increases, and peak flows are adjusted. Second, prevention must take into account hydrological and geomorphological characteristics and be made up of nature-based measures (Van Wesenbeeck *et al.,* 2017). Thirdly, a key aspect of prevention and for social resilience is education of the population, preservation of memory and experience, and awareness of new management paradigms and the adaptive nature of a process that must be continuous over time (Hillman, 2009; Waylen *et al.,* 2018). Along these three lines, our work team advises the CHE within the framework of the Ebro River Resilience strategy.

The Ebro River Resilience strategy can be considered pioneering and original in Spain and is associated with the NWRM (Natural Water Retention Measures) that are promoted at a European level. It is an open strategy, considers the measures it is applying to be experimental, is focused as a learning process, evaluation and monitoring are continuous, responding, therefore, to adaptive management. The concept of resilience is appropriate and is approached from a river and socially integrated perspective (Parsons and Thoms, 2018). However, more ambitious steps are possible, that may perhaps come in the future, such as being able to achieve an authentic fluvial territory in the Middle Ebro River in which the river can flow with greater freedom and recover its erosion processes and, even, meander cutting. In short, to go beyond the flood space that is now being achieved.

It is necessary to evaluate the 120 measures or actions implemented so far, from the aforementioned perspective of learning and adaptive management. Dike removal is the most appropriate and effective measure to provide flood space to the river. It is an action clearly to be expanded in the future, constituting the basis of the new risk management. Temporary controlled flood areas have been very effective in the most recent floods and also have several expansion projects. These measures are concentrated in the vicinity of the settlements of greatest risk, but they will extend throughout the middle course. This is important, because a widespread system of flooding areas is required and only then will the objectives be achieved. The relief channels have shown less efficiency and maintenance is needed, so it is probable that they will not be executed any more. “Curage” is currently the most applied action, since in short, they are small channels of relief that have come to replace the big ones. But it is also a controversial measure as it eliminates natural vegetation. In some cases, it has been rejected or required to only be applied in well-identified flood channels. It is the action that requires more analysis and monitoring.

5. Conclusions

In this current research, the new maximum flow data modified in 2019 by CHE have been applied for the first time. This application has meant a necessary update of the knowledge on the hydrological functioning of the Middle Ebro River. In this new characterization of the floods, on a general level, the changes are not significant, but in detail, some significant and interesting aspects are observed. First, the data change of date (1996) also marks a break in the characteristics of the series, which had higher values and a decreasing trend until 1996, to change to a slightly increasing trend since 1996. Second, there are variations in the frequency of events: up to 1996 there were more floods (1 per year on average) than since 1996 (0.65 per year). However, the number of flow points is 2 per event until 1996 and increases to 2.13 in series 2. In this second series, the floods are a little longer and more complex. In Zaragoza gauging station floods presented in 1996-2019 more total volume, more bankfull days and more episodes above the flow rate of sediment mobilization. Regarding seasonality, current floods are concentrated in winter and spring, with the autumn ones having disappeared. Lastly, the correction of data and the extension of the series have meant an update of the return periods, reducing the expected flow for the reference periods.

In any case, the average or most common flood in the Middle Ebro River, according to the new series 2 (1996-2019) and in Zaragoza (maximum reliability gauging station), would occur in February, has two peaks, reaches about 1800 m^3 s^{-1}, lowered about 300 m^3 s^{-1} its peak flow due to overflows occurring from the confluence of the Aragón River, exceeds the bankfull level during 40 hours and the threshold of sediment mobilization lasts 19 days, and moves 2225 hm^3 of water in total.

Consequently, the danger remains fairly stable, but the duration of each flood has increased, as well as the transit time. Damage may be greater due to the longer duration of the flood. This is one of the arguments for implementing new management measures, highlighting the increase of on-site storage capacity.

In the recent evolution of the Middle Ebro River, a correlation between some extreme events and the social and management response has been observed, so that in integrating the main floods registered with the procedures and measures carried out, 4 phases have been identified: i) until 1945 without regulation and with few bank protection actions, ii) maximum action against the river (1945-1990), iii) scientific awareness (1990-2015), iv) current phase of change (2015-2020) with the implementation of FRMP and the Ebro River Resilience strategy. The measures of this implementation stand out for following the paradigm of giving more space to the river, and increasing the lowering capacity of floods in the river section itself.

In this context, the present work marks a starting or turning point laying the foundations i) towards new analyses that will have to be developed when the reviewed hydrological series are prolonged in time, ii) towards the follow-up and adaptive evaluation of the new risk management measures that are being implemented, so that they are sustainable and achieve river resilience, and iii) greater knowledge of floods and risk, which must be conveyed to the population so that it increases its memory, awareness and with it, their resilience.

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RAINFALL AND WATER YIELD IN MACIZO DEL CAROIG, EASTERN IBERIAN PENINSULA. EVENT RUNOFF AT PLOT SCALE DURING A RARE FLASH FLOOD AT THE BARRANCO DE BENACANCIL

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ABSTRACT. Floods are a consequence of extreme rainfall events. Although surface runoff generation is the origin of discharge, flood research usually focuses on lowlands where the impact is higher. Runoff and sediment delivery at slope and pedon scale receiving much less attention in the effort to understand flood behaviour in time and space. This is especially relevant in areas where, due to climatic and hydrogeological conditions, streams are ephemeral, so-called dry rivers (“wadis”, "ramblas" or “barrancos”) that are widespread throughout the Mediterranean. This paper researches the relationship between water delivery at pedon and slope scale with dry river floods in Macizo del Caroig, Eastern Iberian Peninsula. Plots of 1x1, 1x2, 1x4, and 2x8 m located in the “El Teularet” Soil Erosion and Degradation Research Station were monitored from 2004 to 2014 to measure soil and water delivery. Rainfall and flow at the dry river Barranco de Benacancil were also monitored. Results show that runoff and sediment discharge were concentrated in few events during the 11 years of research. A single flood event was registered in the channel on September 28, 2009, however, the runoff was registered 160 times at the plots. Runoff discharge was dependent on the size of the plots, with larger plots yielding lower runoff discharge per unit area, suggesting short runoff-travel distance and duration. Three rainfall events contributed with 26% of the whole runoff discharge, and five achieved 56% of the runoff. We conclude that the runoff generated at the plot scale is disconnected from the main channel. From a spatial point of view, there is a decrease in runoff coefficient along the slope. From a temporal point of view, the runoff is concentrated in a few rainfall events. These results show that the runoff generated at plot and slope scale does not contribute to the floods except for rainfall events with more than 100 mm day^{-1}. The disconnection of the runoff and sediment delivery is confirmed by the reduction in the runoff delivery at plot scale due to the control of the length of the plot (slope) on the runoff and sediment delivery.

Precipitación y producción de agua en el Macizo del Caroig, Este de la Península Ibérica. Evento de escorrentía a escala de parcela durante una crecida torrencial en el barranco de Benacancil

RESUMEN. Las inundaciones son consecuencia de lluvias extremas. Aunque la generación de escorrentía superficial es el origen de la descarga, la investigación de inundaciones generalmente se enfoca en las tierras bajas donde el impacto es mayor. La escorrentía y la distribución de sedimentos a escala de pendiente y pedón reciben mucha menos atención en la comprensión del comportamiento de las inundaciones en el tiempo y el espacio. Esto es especialmente relevante en zonas donde, debido a las condiciones climáticas e hidrogeológicas, los cauces son efímeros. Son los llamados ríos secos (“wadis”, “ramblas” o “barrancos”) muy extendidos por todo el Mediterráneo. Este artículo investiga la relación entre el suministro de agua a escala de pedón y ladera con las crecidas de ríos secos en Macizo del Caroig, este de la Península Ibérica. Las parcelas de 1x1, 1x2, 1x4 y 2x8 m localizadas en la Estación de Investigación de Erosión y Degradación de Suelos “El Teularet” fueron monitoreadas de 2004 a 2014 para medir la producción de suelo y agua. También se monitorearon las precipitaciones y el caudal en el río seco Barranco de Benacancil. Los resultados muestran que la escorrentía y la descarga de sedimentos se concentraron en pocos eventos durante los 11 años de investigación. Se registró un solo evento de inundación en el canal el 28 de septiembre de 2009, sin embargo, la escorrentía se registró 160 veces en las parcelas. La descarga de escorrentía dependió del tamaño de las parcelas. Las parcelas más grandes produjeron una menor descarga de escorrentía por unidad de área, lo que sugiere una corta distancia y duración del recorrido de escorrentía. Tres eventos de lluvia contribuyeron con el 26% de la descarga total de la escorrentía y cinco lograron el 56% de la escorrentía. Se concluye que la escorrentía generada a escala de la parcela está desconectada del canal principal. Desde un punto de vista espacial, hay una disminución en el coeficiente de escorrentía a lo largo de la pendiente. Desde un punto de vista temporal, la escorrentía se concentra en unos pocos eventos de lluvia. Estos resultados muestran que la escorrentía generada a escala de parcela y pendiente no contribuyen a las inundaciones excepto para eventos de lluvia con más de 100 mm día^{-1}. La desconexión de la escorrentía y la entrega de sedimentos se confirma por la reducción de la escorrentía a escala de parcela debido al control de la longitud (pendiente) sobre la escorrentía y la entrega de sedimentos.

Key words: Runoff, sediments, rainfall, extreme events, dry rivers, ephemeral floods.

Palabras clave: escorrentía, sedimentos, precipitación, eventos extremos, ríos secos, inundaciones efímeras.

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1. Introduction

Floods are a consequence of the interaction of nature and humans (Hamilton, 1987). Nature determines that lowlands and other areas prone to be flooded along the catchments will be covered by water during some periods due to extreme rainfall events (Downs and Thorne, 2000). Human activities taking place in the floodplain, as well as wrong planning and land use mismanagement the upstream, can increase the economic damage and casualties caused by floods.

Within the factors that control flood events, extreme rainfall is the most relevant (Guhathakurta *et al.,* 2011). Extreme rainfall events, either in volume or intensity, result in extreme floods (Smith *et al.,* 2001). This has been documented at different scales, from large basins (Parida *et al.,* 2017) to small watersheds (Daliakopoulos and Tsanis, 2012). Most of the research carried out in areas affected by floods focuses on the lowlands as they are the areas that suffer more and where the damages from a life and property point of view are higher (Bauer *et al.,* 2018). However, damages from floods in mountainous terrain, from small creeks, are becoming more frequent (Wu *et al.,* 2019). Moreover, the lowlands are also very dynamic from the fluvial and geomorphological perspective (Keesstra, 2007; Kalantari *et al.,* 2018; Yousefi *et al.,* 2018). Although most of the attention by policymakers, land-users, and practitioners after a flood is located in the lowlands, from a geomorphological and hydrological point of view, the runoff delivery from the upper mountainous areas is relevant to understand the mechanism of the floods and to learn how to prevent them.

It is accepted that the origin of the floods can be found in the runoff generated at pedon and slope scale, although few papers focuss on this origin of the runoff discharge that can result in dramatic events. In northern France, Martin (1999) researched the effect of agriculture practices (no-tillage, moldboard plowing, mustard intercrops, and superficial plowing) on runoff production and soil loss and found a positive effect of the use of cover crops to control floods. Hümann *et al.* (2011) in the forest land of Southwest Germany found that forest land contributes to reducing the floods as runoff was higher in the agricultural land. Similar findings in the Loess Plateau in China were measured by Zhang *et al.* (2018) who analyzed 371 flood events (1963-2011) and demonstrated that floods accounted for 49.6% to 91.8% of their mean annual totals of runoff. The reduction of surface runoff and associated sediment yield in floods explained about 85.0% to 89.2% of the sediment yield.

The connection between soil erosion and floods is a classic topic in soil erosion research that is much less studied in recent years. Robinson and Blackman (1990) researched soil erosion of arable farmland on the South Downs in East Sussex that used to cause episodic flooding and they demonstrated that the on-farm costs of the erosion were smaller than the off-farm costs. Bannari *et al.* (2016) assessed the flash-flood impact on soil redistribution in the foot of the western Anti-Atlas Mountains in the south of Morocco. Wilkinson *et al.* (2010) show the impact of floods in the runoff in the Belford catchment in Northumberland and Bronstert *et al.* (1995) in Germany and Saghafian *et al.* (2008) in the Golestan region of Iran. The research of Poesen and Hooke (1997) in the Mediterranean updated the knowledge on soil erosion and flood issues with a general overview. Other researchers contributed with regional data to understand how runoff is generated and floods formed. The works of Romero-Diaz *et al.* (2010) contributed key information to understand how the afforestation in semiarid land can result in higher erosion rates. Ecosystems response to soil erosion and flood generation is complex such as the land abandonment show (Romero-Díaz *et al.,* 2017) along climatological gradients in Mediterranean ecosystems (Ruiz-Sinoga and Díaz, 2010). Dry rivers (ephemeral rivers) are studied from different perspectives in the Mediterranean region: flood events; channel changes; and mapping upon land-use indicators (Yousefi *et al.,* 2020)). But little research has been developed to link the runoff and sediment detached at pedon and slope scale with the floods triggered on the talweg.

An example of the connection between the pedon and watershed-scale takes place during extreme rainfall events such as the one on September 12, 2019, when 300 mm were registered in Ontinyent, Spain, in one day (see Fig. 1). Similar examples can be found in the review of López-Bermúdez (1993) when rainfall events of high magnitude – low frequency are analyzed. Then the overland flow was extreme in the river Canyoles with a flash flood and evidence (rills and gullies) found in the headwaters of the watershed. The key scientific question here is the frequency of these extreme rainfall events. These events have also formed most of the geomorphologic features of the Mediterranean Type-Ecosystems, and this is relevant as they determine also the landforms. To answer this key scientific and development question, we need long-term measurements in the field and an assessment of the floods. Long-term monitoring is the key contribution of this paper.

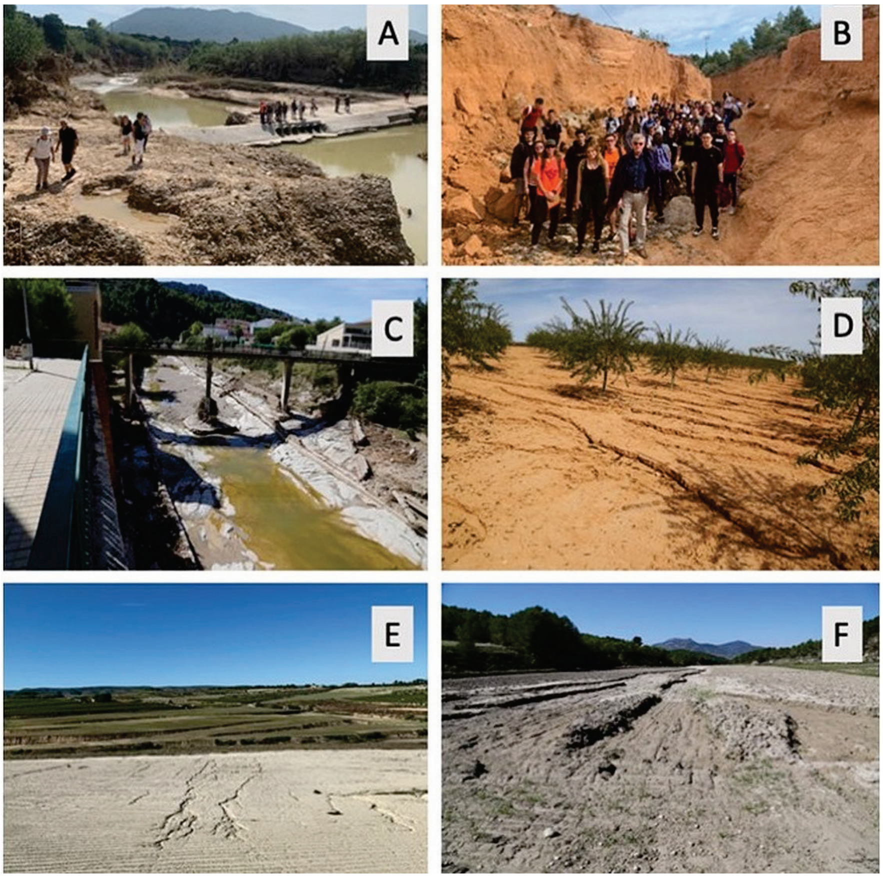

Figure 1. Views of the impact of the DANA of 12 September 2019 at the study are of river Canyoles watershed. View of the river Canyoles talweg after the flood in Granja de la Costera, (A), gully formed as a consequence of the mismanagement of the railway flows at Font de la Figuera (B), talweg of the river Canyoles in Moixent with the removal of the sediments (C), almond plantation affected by rilling in Font de la Figuera (D), rill development in sunflower fields in Moixent (E), and barley field after tillage with wide gullies in Font de la Figuera (F).

Previous research approached this topic at a single spatial scale. This was the conventional approach. However, recently some authors applied different techniques to determine the runoff and soil losses at different scales. To develop a better understanding of the floods in Japan and to determine how the forest management practices determine the runoff generation, sediment transport, and soil erosion, Onda *et al.* (2010) conducted field observations and monitored the discharge, water quality, and soil erosion in forest plantations through catchments (> 4 ha), plots (0.1-4 ha), hillslope plots (0.5-2 m) and splash cups. The effect of the scale is relevant such as was found by Bagarello *et al.* (2018) where plots of different sizes resulted in runoff coefficients and soil erosion with different orders of magnitude. The larger the plot, the lower the soil losses, which is due to the low degree of connectivity of the flows (Keesstra *et al.,* 2018). The importance of the plot size was also a key factor during the recovery of the plant cover after land abandonment such as Cerdà *et al.* (2018) found in El Teularet research station. Floods are also enhanced by human activities in the headwaters of the watersheds and basin. Deforestation has been one of the main human impacts on the mountain terrains that enhanced floods and activated the erosional cycle and result in fluvial adjustments (Begueria *et al.,* 2006). Although other factors are relevant to understand and foresee the runoff generation during floods, extreme rainfall events are the ones that trigger the runoff initiation, sheet and rill flows, and finally the floods (Smith *et al.,* 2011).

Most of the research was carried out at a watershed scale to determine the runoff discharge and sediment delivery. The contribution at slope and pedon scale is much less researched to understand flood behavior in time and space, although the runoff generation at smaller scales is the origin of the large-scale water discharge. This paper researches the role of low frequency-high magnitude events in the water delivery at pedon and slope scale on flood generation in Mediterranean mountainous terrains.

2. Material and Methods

2.1. Study area

Macizo del Caroig was selected to determine the soil erosion and water yield in a typical Mediterranean mountainous area dominated by rainfed agriculture and rangelands. There, the Department of Geography (University of Valencia) developed in 2002 the El Teularet Soil Erosion and Degradation Research Station to monitor and assess the impact of land management and land uses on soil erosion and runoff generation (Fig. 2). Climate is the typical Mediterranean with a mean annual temperature of 12.7°C registered at the nearby Las Arenas Enguera meteorological station. January is the coldest month (9.8°C) and August is the warmest (25.7°C). Rainfall is characterized by a mean annual rainfall of 540 mm and a typical Mediterranean dry summer. The highest rainfall intensities were recorded from September to December when some rainfall events with a 10-year return period can reach 100 mm day^{-1} (Cerdà, 2017). Four erosion plots were installed on a slope of marl parent materials which used to be agricultural land. The overall landforms are characterized by a succession of plateaus and deeply incised valleys. This is a consequence of the weathering (dissolution) of the Cretaceous carbonate rocks which are the main parent material in the study area and Eastern Spain; on patches of marls in the landscape, most of the (abandoned) agriculture fields can be found. Soils at the study site are classified as Typic Xerorthents (Soil Survey Staff, 2014) (Cerdà *et al.,* 2018).

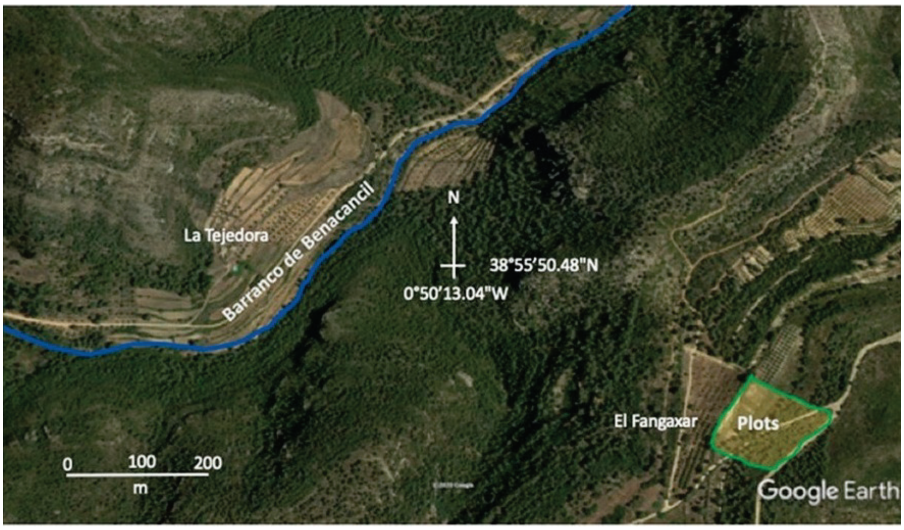

Figure 2. Location of the study sites. The main creek is Barranco de Benacancil located 706 m from the soil erosion plots in the Macizo del Caroig, inland Valencia province.

2.2. Methods

A set of 4 plots was established in 2002. Plots were delineated with aluminium sheets, 1 mm thick by 50 mm height, that prevented surface and subsurface flow to and from each catchment. Each plot consisted of 1x1, 1x2, 1x4, and 2x8 m (width x length) (Fig. 3). The plots were tilled 4 times per year (April, May, June, and August) to remove vegetation as traditionally done for soil management of almond, fruit, olive, and vineyard crops in the region. The first measurements took place in January 2004. After each rainfall event, runoff discharge and runoff sediment concentration were measured, and plots borders, drainage, collectors, pipes, and deposits were checked for damages.

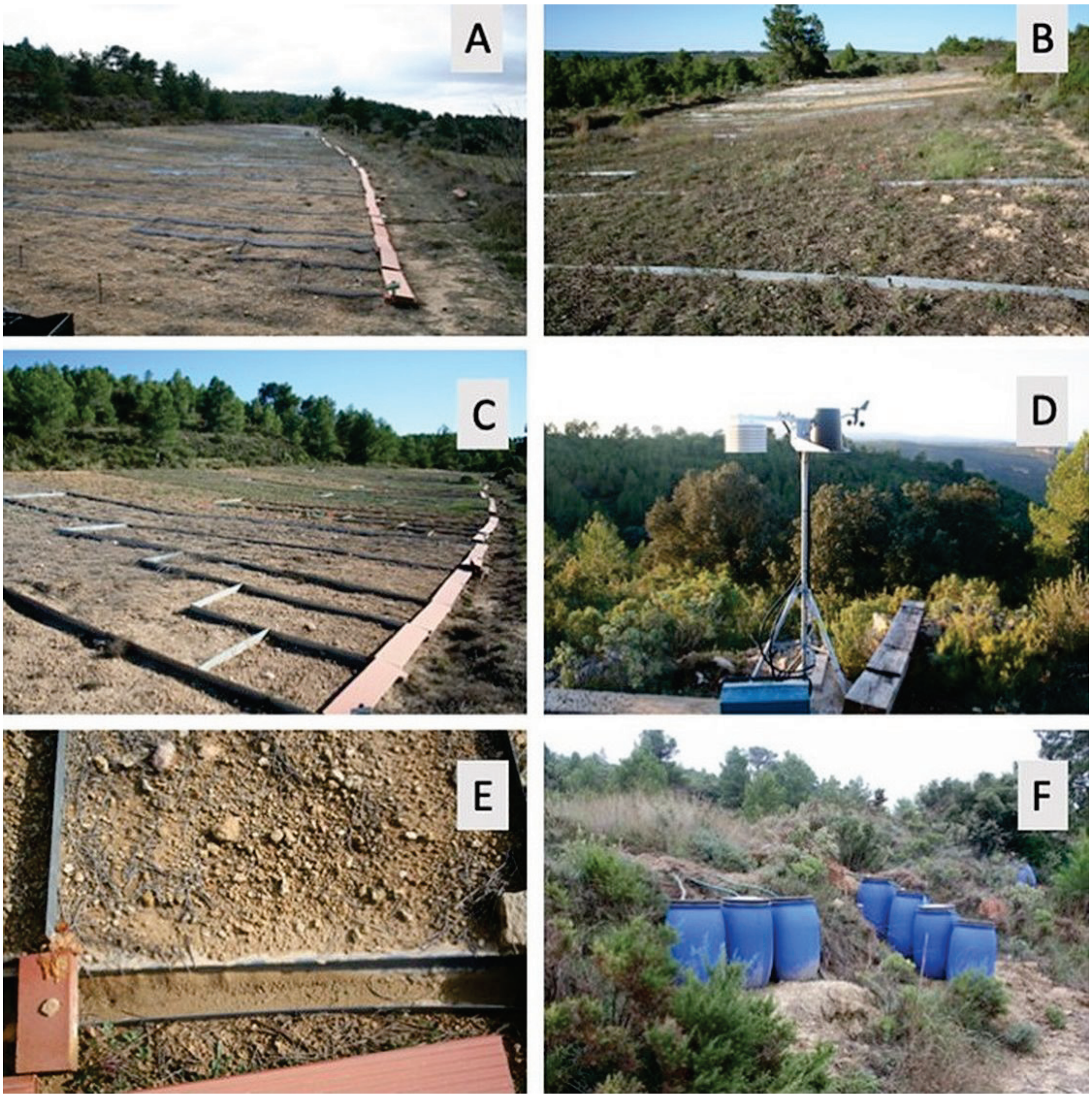

Figure 3. View of the plots in January 2006 (A), April 2007 (B), and May 2008 (C), meteorological station in October 2005 (D), detail of one of the collectors in June 2007 (E) and runoff deposits in July 2008 (F).

Soil and vegetation descriptions and sampling were made in December 2003 before the measurements were initiated and maintained during the experimental period. Rainfall (mm) was measured in the nearby Las Arenas meteorological station located 5 km from the study site. More than 6 hours without rainfall was used as the threshold to determine the rainfall events. Runoff (l) was collected from the plots using a collector (gutter) that was 0.15 x 1 m (2 m in the 16 m^2 plots, 2 x 8 m^2) and 0.15 m depth. The collected runoff was drained into 125 and 250 l tanks connected to the collector by a 0.4 m-diameter pipe. Total storage capacities were 125, 250, 375, and 600 l for the 1, 2, 4, and 16 m^2 plots, respectively.

3. Results and Discussion

The measurements carried out in El Teularet Soil Erosion and Degradation Research Station during the 11 years of the study untangle the connectivity regime of the flows along the slope, and from the slope to the stream Barranco de Benacancil.

3.1. Rainfall

The total rainfall measured during the 11 years of research reached 6,280.8 mm. The rainfall distribution per year shows that although the average rainfall was 571.0 mm for the eleven-year study period, the variability was very high as it ranged from 288.0 mm in 2005 to 749.0 mm in 2007. The seasonal distribution of rainfall was characterized by dry summers which are typical in the Mediterranean ecosystems and last from July to August (Vicente-Serrano *et al.,* 2004; López-Moreno *et al.,* 2009). The negative trend of the mean annual rainfall was not significant (y: -3.13x + 6,848.2; R^2: 0.0058) but the period is too short to conclude that there is a trend. Although changes in the rainfall trend in the Mediterranean have been observed, they are not registered in other Western Mediterranean long-time series of data (Peña-Angulo *et al.,* 2020). The decrease in annual rainfall found by other authors is paradoxical with the increase in the mean daily rainfall (Alpert *et al.,* 2020). Those changes will affect the vegetation growth and then the soil and water yield in Mediterranean Ecosystems (Sarris *et al.,* 2007; Keesstra *et al.,* 2009).

The largest daily rainfall events at the El Teularet study site took place in 2009 (140.0 mm) and 2013 (111.0 mm). The largest rainfall events (consecutive rainy days) amounted to 230.0 mm in 2009, 176.8 mm in 2012, and 167.0 mm in 2004 (Table 1). Daily rainfall has been increasing in the Mediterranean (Ribes *et al.,* 2019) although not in all the regions (Serrano-Notivoli *et al.,* 2018) were found the same trend. The highest rainfall events show a good correlation with the highest mean annual rainfall at the study area such as has also been found in other research sites (Mathbout *et al.,* 2018) (Fig. 4).

Table 1. Rainfall distribution per year and for the 1st, 2nd, and 3rd largest daily rainfall and rainfall event.

Year	**Total** **mm**	**Day 1st** **mm**	**Day 2nd** **mm**	**Day 3rd** **mm**	**Event 1st** **mm**	**Event 2nd** **mm**	**Event 3rd** **mm**
2004	699.8	66.0	49.0	43.5	167.0	110.5	62.5
2005	288.0	44.0	31.5	18.0	44.0	31.5	19.8
2006	485.0	64.0	50.0	30.0	89.9	88.0	50.0
2007	749.0	80.0	68.0	67.0	131.0	80.0	68.0
2008	609.4	58.0	52.0	52.0	119.0	66.0	65.5
2009	728.5	140.0	52.0	51.5	230.0	59.2	58.0
2010	554.2	45.0	32.3	31.5	48.2	33.5	33.4
2011	590.4	93.0	49.0	35.0	145.5	83.5	70.0
2012	593.7	90.0	90.0	70.0	176.8	98.0	70.0
2013	560.4	111.0	90.0	48.0	111.0	100.5	70.0
2014	422.4	48.1	41.0	38.6	72.9	48.1	41.0
Average	**571.0**	**76.3**	**55.0**	**44.1**	**121.4**	**72.6**	**55.3**
Max	**749.0**	**140.0**	**90.0**	**70.0**	**230.0**	**110.5**	**70.0**
Min	**288.0**	**44.0**	**31.5**	**18.0**	**44.0**	**31.5**	**19.8**

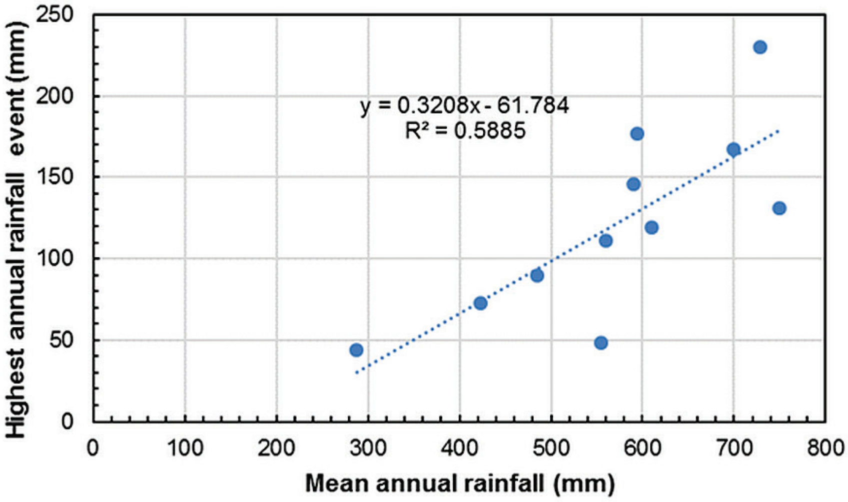

Figure 4. Relation between mean annual rainfall and highest daily rainfall and vice versa.

The daily rainfall for the period from September 12, 2009, to September 30, 2009, accounted for 340.5 mm with 230.0 mm from September 27th to September 30th and 140.0 mm on September 28th. This extreme rainfall event accounted for 46% of the total rainfall in 2009, which was a wet year with a total of 728.5 mm mainly due to this extreme rainfall event. The rainfall events of September 2009 accounted for 5.4% of the total rainfall registered in the study area from 2004 to 2014. Table 2 shows the daily distribution of the rainfall from September 12 to September 30, 2009.

Table 2. Rainfall per day and for the five events registered during the rainy season of September 2009. On September 9th we registered a flash flood at the ephemeral stream of Barranco de Benacancil.

Period Days 10	Daily Rainfall mm	Event Rainfall mm
12.9.09	7.0	
13.9.09	24.0	31.0
15.9.09	14.5	14.5
17.9.09	10.5	10.5
22.9.09	36.0	
23.9.09	18.5	54.5
27.9.09	52.0	
28.9.09	140.0	
29.9.09	11.0	
30.9.09	27.0	230.0
Total	**340.5**	**340.5**

The rainfall event of September 2009 was relevant as during the experimental period (2002-2014) we registered very dry years such as 2005 when 288 mm were recorded. The 140 mm registered on September 28th is not a rare event. Other extreme events have taken place in the area, e.g. October 21-22, 1982, with 623 mm in two days registered in Casa del Barón en la Muela de Cortes de Pallas and 580 mm in the nearest town (Enguera). The October 1982 precipitation event led to a catastrophic Xúquer river flood and the collapse of Tous Dam and the flood of the La Ribera district.

The distribution of the rainfall at El Teularet during the research period is shown in Figure 5, for daily and event measurements, respectively.

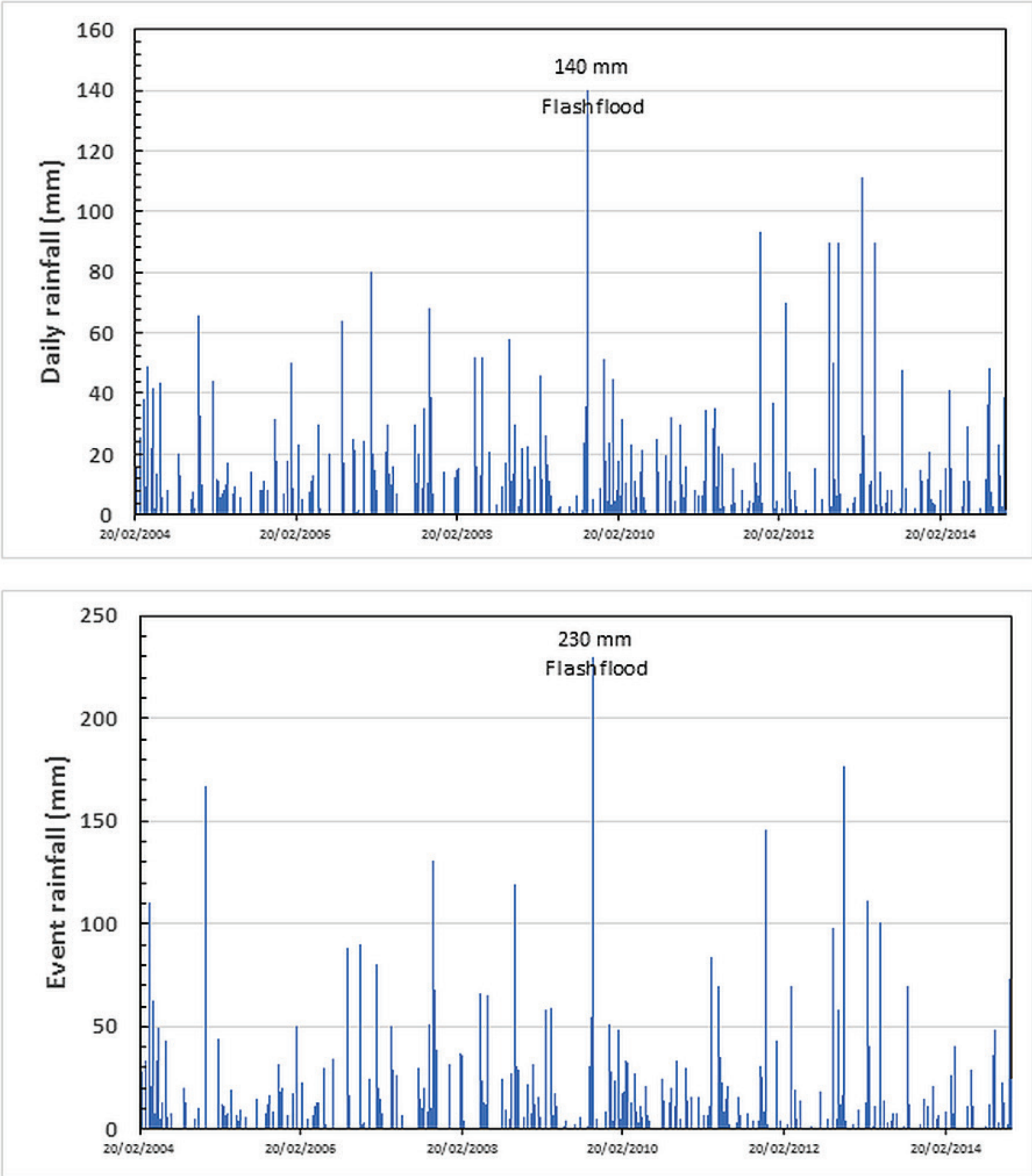

Figure 5. Daily rainfall (mm) at the El Teularet Soil Erosion and Degradation Research Station.

3.2. Runoff

During the entire 11 years of the study, the stream Barranco de Benacancil had runoff discharge only on September 28, 2009, after 140 mm of rainfall in one day. The discharge was a flash flood such as was described by farmers due to the sudden arrival of the runoff discharge wave. However, the runoff discharge at the plots under tillage in the El Teularet Soil Erosion and Degradation Research Station contributed to 169 runoff events during the 11 years of the study.

Annual runoff was measured at each of the four plots of 1, 2, 4, and 16 m^2. The total runoff during the 11 years (6,280.8 mm of rainfall) amounted to 868.5, 1,066.7, 1,438.7, and 3,678.4 l for the 1, 2, 4, and 16 m^2 plots, respectively. Annual variability was high, with the dry year 2005 yielding 9.8, 13.8, 20.8, and 40.4 l and wet 2007 yielding 176.1, 208.6, 300.7, and 708.1 l of runoff for the 1, 2, 4, and 16 m^2 plots, respectively (Table 3).

Table 3. Runoff discharge per plot and year (l). Total and average values.

Plot Surface Year	Plot 1 1 m^2 (l)	Plot 2 2 m^2 (l)	Pot 3 4 m^2 (l)	Plot 4 16 m^2 (l)	All plots 23 m^2 (l)
2004	138.6	181.7	227.5	677.7	1,225.5
2005	9.8	13.8	20.8	40.4	84.8
2006	74.3	101.1	171.9	344.0	691.3
2007	176.1	208.6	300.7	708.1	1,393.5
2008	69.3	78.5	122.6	262.0	532.4
2009	124.7	155.4	223.1	620.2	1,123.4
2010	20.8	27.4	30.8	70.3	149.4
2011	44.2	53.2	66.3	148.4	312.1
2012	122.4	139.7	150.4	434.2	846.7
2013	65.4	80.2	88.2	280.9	514.6
2014	22.9	26.9	36.5	92.3	178.6
Total	868.5	1,066.7	1,438.7	3,678.4	7,052.3
Average	79.0	97.0	130.8	334.4	641.1

Runoff discharge measured during the 11 years of research shows that the discharge is dependent on the plot size. Table 4 show that the total runoff per plot upon the 6,280.8 mm of rainfall move from the 868.5 mm till the 533.3, 359.7, and 229.9 l m^{-2}, with an average of 497.8 l m^{-2} (Table 4).

Table 4. Runoff discharge per plot and year (mm). Total and average values.

Plot Surface Year	Plot 1 1 m^2 (mm)	Plot 2 2 m^2 (mm)	Pot 3 4 m^2 (mm)	Plot 4 16 m^2 (mm)	All plots 23 m^2 (mm)
2004	138.6	90.9	56.9	42.4	82.2
2005	9.8	6.9	5.2	2.5	6.1
2006	74.3	50.6	43.0	21.5	47.3
2007	176.1	104.3	75.2	44.3	99.9
2008	69.3	39.3	30.7	16.4	38.9
2009	124.7	77.7	55.8	38.8	74.2
2010	20.8	13.7	7.7	4.4	11.7
2011	44.2	26.6	16.6	9.3	24.2
2012	122.4	69.9	37.6	27.1	64.3
2013	65.4	40.1	22.0	17.6	36.3
2014	22.9	13.4	9.1	5.8	12.8
Total	868.5	533.3	359.7	229.9	497.8
Average	79.0	48.5	32.7	20.9	45.3

The runoff coefficient also shows that runoff discharge is dependent on plot size. In average values, a decrease in the runoff coefficient is observed from 12.1, 7.8, 5.3, and 3.3% for the 1, 2, 4, and 16 m^2 plots, respectively (Table 5).

Table 5. Runoff coefficient per plot and year (%). Total and average values.

Plot	Plot 1	Plot 2	Pot 3	Plot 4	All plots
Surface	**1 m^2**	**2 m^2**	**4 m^2**	**16 m^2**	**23 m^2**
Year	**(%)**	**(%)**	**(%)**	**(%)**	**(%)**
2004	19.8	13.0	8.1	6.1	11.7
2005	3.4	2.4	1.8	0.9	2.1
2006	15.3	10.4	8.9	4.4	9.8
2007	23.5	13.9	10.0	5.9	13.3
2008	11.4	6.4	5.0	2.7	6.4
2009	17.1	10.7	7.7	5.3	10.2
2010	3.7	2.5	1.4	0.8	2.1
2011	7.5	4.5	2.8	1.6	4.1
2012	20.6	11.8	6.3	4.6	10.8
2013	11.7	7.2	3.9	3.1	6.5
2014	5.4	3.2	2.2	1.4	3.0
Average	12.7	7.8	5.3	3.3	7.3

The influence of the scale of measurement on runoff generation has been measure in a few research sites. The review of De Vente and Poesen (2005) on this topic demonstrated that the scale is a factor of the soil erosion rate measured. Most of the approaches to this topic were developed at catchment or basin scale (Bhattarai and Dutta, 2007), and much less information is found at the plot scale. Bagarello *et al.* (2018) already found in similar plots (under herbicide treatment) a strong control of the length of the slope: as longer the slope lower is the soil losses. Smets *et al.* (2008) found that the length of the plots (0.5 to 31.5 m) control the effectiveness of the mulches to control the soil and water losses. Kirkby (2010) already highlighted the importance of the distance on the slope, and scale effect, when researching the soil erosion processes. Parson *et al.* (2006) used eight runoff plots (2-28 m length) in Walnut Gulch Experimental Watershed in southern Arizona to determine that the sediment yield increased until 7 m plot length and later decreased. Santos *et al.,* (2017) developed research in the semiarid region of Brazil with 116 rainfall events with plots of 1, 20, and 28,000 m^2 to determine the impact of slash and burn on soil erosion. They found that the highest water losses were measured at 20 m^2 plots. Cammeraat (2004) utilizing a nested approach that the runoff was initiated under lower rainfall intensities at the pedon scale than at the slope (and watershed) scale in the Murcia region of the Eastern Iberian Peninsula. Moreno de las Heras *et al.* (2010) used length plots from 1 to 15 m on reclaimed land and they agree that a general decrease of unit area runoff was observed with increasing plot scale for all slopes. Langhans *et al.,* (2019) studied the impact of conservation tillage on different plot sizes (5, 30, and 180 m^2) and found that as larger were the plots lower the runoff coefficient, and that the impact of the management was affected by the scale of measurement.

In the El Teularet soil erosion experimental station we found a similar behavior of the plots: a reduction in the runoff delivery per unit area from the small to the large plots. Figure 6 shows a decrease in the runoff discharge (mm) from the 1 m^2 plots to the ones with 16 m^2. The maximum values registered in 2007 show this trend under the wettest conditions and year 2005 during the driest conditions. For the runoff coefficient (%) the trend shows how runoff is reduced by three times from 1 to 16 m^2 (Fig. 7). Figure 6 shows the trend along with the changes in the scale of the total runoff (l). The increase is because the plots are larger, but the runoff per unit area (% or mm) shows a reduction such as figures 6 and 7 shown.

The total rainfall at year scale influences the total runoff. The largest runoff coefficients were registered in the wettest year (2007) with 23.5, 13.9, 10, and 5.9%, and the lowest in 2005 with 3.4, 2.4, 1.8, and 0.9 % for the 1, 2, 4, and 16 m^2 plots. The relation between the rainfall and runoff also is affected by the control that the size of the plots exerts on the runoff yield. We found that within the relation between rainfall and runoff the size of the plots also is relevant (Fig. 7).

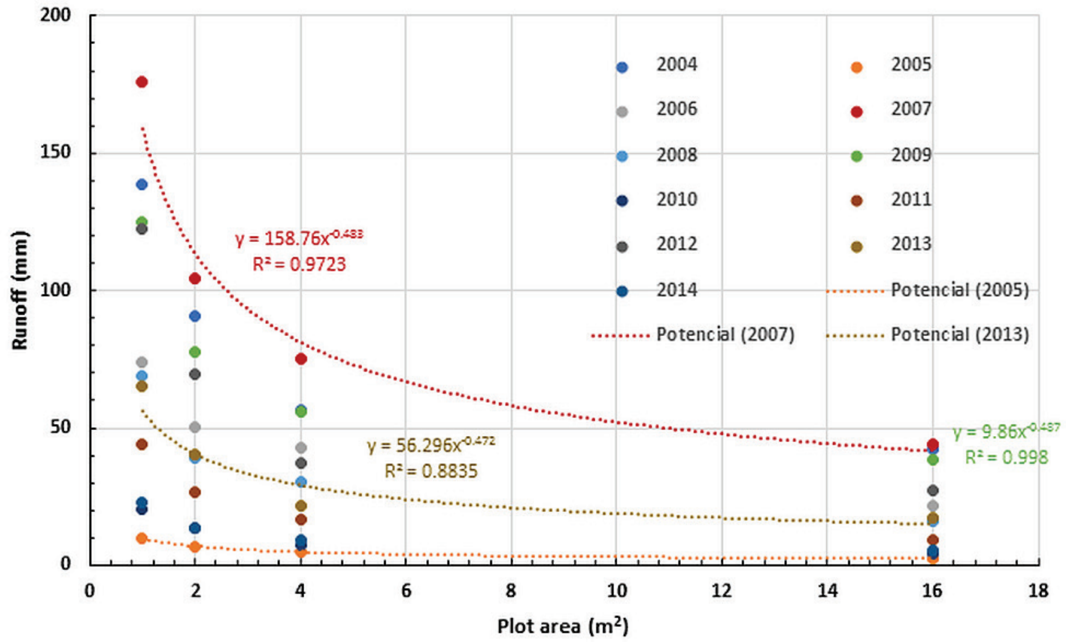

Figure 6. Event rainfall (mm) at the El Teularet Soil Erosion and Degradation Research Station.

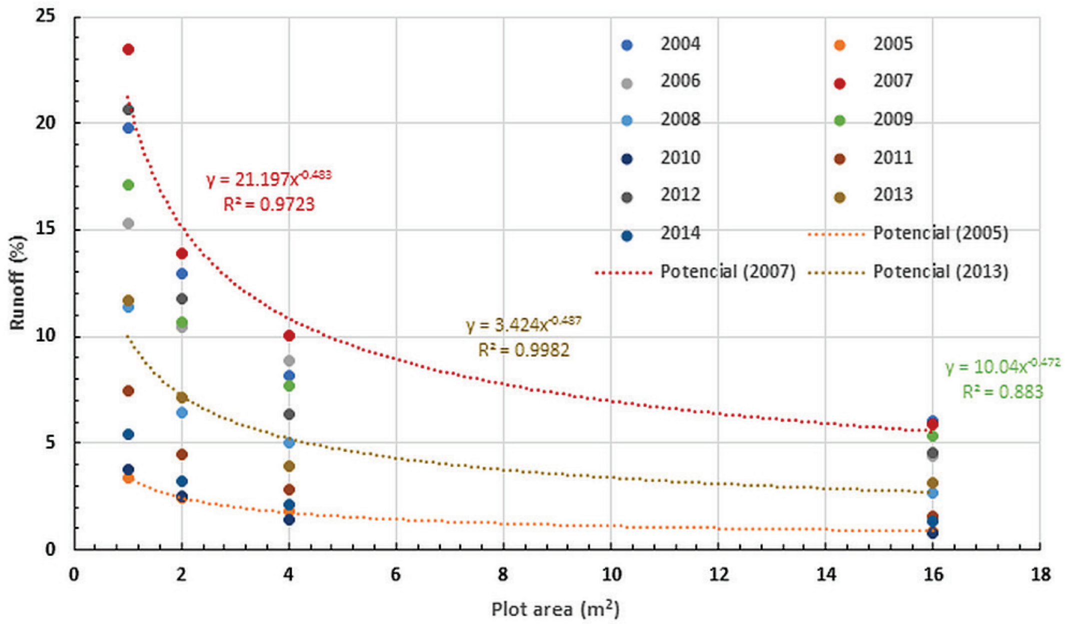

Figure 7. Runoff discharge (l) per year and plot per size of the plots (m^2).

3.3. Event rainfall and runoff

The runoff collected in the 4 plots during the runoff events shows that the runoff events do not take place when the rainfall is below 10 mm. Although we registered 470 daily rainfall grouped in 311 events, only 169 events were effective to deliver runoff, which is an average of 15.4 runoff events per year. Within the 311 rainfall events recorded (28.3 per year), 140 events of rainfall did not contribute to runoff due to the low rainfall volume below10 mm. Within the 109 rainfall events between 10 and 30 mm, 107 rainfall events contributed to runoff. All the rainfall events with rainfall values higher than 30 mm contributed to runoff (Table 6).

Table 6. Rainfall and runoff event distribution (nº, mm, %) for the 4 plots at the El Teularet Soil Erosion and Degradation Research Station.

Ranks	**Rainfall nº**	**Rainfall mm**	**Rainfall Event nº**	**Rainfall Event mm**
>100	2	251.0	9	1,291.3
>60	11	842.0	14	1,046.8
>30	41	1,649.8	39	1,548.5
>10	153	2,397.7	109	1,752.7
>5	122	809.8	71	470.8
>0	141	330.5	69	170.7
Total	**470**	**6,280.8**	**311**	**6,280.8**

Ranks	**Runoff Event nº**	**Runoff Event mm**	**Runoff Event mm**	**Runoff Event mm**	**Runoff Event mm**
		1 m²	**2 m²**	**4 m²**	**16 m²**
>100	9	458.0	273.1	176.4	133.6
>60	14	198.0	121.8	85.0	41.8
>30	39	145.4	93.0	63.8	36.7
>10	107	67.1	45.5	34.6	17.8
>5	0	0.0	0.0	0.0	0.0
>0	0	0.0	0.0	0.0	0.0
Total	**169**	**868.5**	**533.3**	**359.7**	**229.9**

Ranks	**Runoff Average %**	**Runoff 1 m² %**	**Runoff 2 m² %**	**Runoff 4 m² %**	**Runoff 16 m² %**
>100	52.8	52.7	51.2	49.0	58.1
>60	21.9	22.8	22.8	23.6	18.2
>30	17.0	16.7	17.4	17.7	16.0
>10	8.4	7.7	8.5	9.6	7.7
>5	0.0	0.0	0.0	0.0	0.0
>0	0.0	0.0	0.0	0.0	0.0
Total	**100**	**100**	**100**	**100**	**100**

The runoff yield (mm) was determined by the size of the plot, but the runoff initiation did not. All the plots have shown that when runoff took place, the runoff was present in all plots, which is because under tillage conditions the soils contribute to surface runoff when the rainfall intensity is higher than the soil infiltration capacity (Horton, 1933). The Hortonian overland flow mechanism induces that when runoff is present it is found along the whole slope. In agricultural land, Hortonian overland flow is generated due to the impact of tillage that reduces that induce soil degradation, the formation of surface crusts, and then the runoff initiation. Ziegler *et al.* (2001) found that Hortonian overland flow was present in an agriculture watershed in northern Thailand where the soil hydraulic conductivity was low. The low infiltration rates of the soils are the key factor to enhance the Hortonian overland flow (Dunne and Dietrich, 1980). Agriculture land induces low infiltration rates and high runoff discharges. This has been found in areas where tillage is present. Tillage induces the degradation of the soils in different regions of the world and induced the highest runoff discharges and also quick overland flow. Chalise *et al.,* (2019; 2020) found this in Nepal, Cerdà *et al.,* (2020) in eastern Spain, Takken *et al.,* (2001) in the loess belt in Europe, and Tullberg *et al.,* (2001) in Australia.

On the other hand, the magnitude of the runoff discharge was determined by the size of the plot as the larger plots contributed with the lowest runoff discharge (per unit area, mm); however, the total amount of runoff in the larger plots was higher as the contribution area was larger (see Fig. 8).

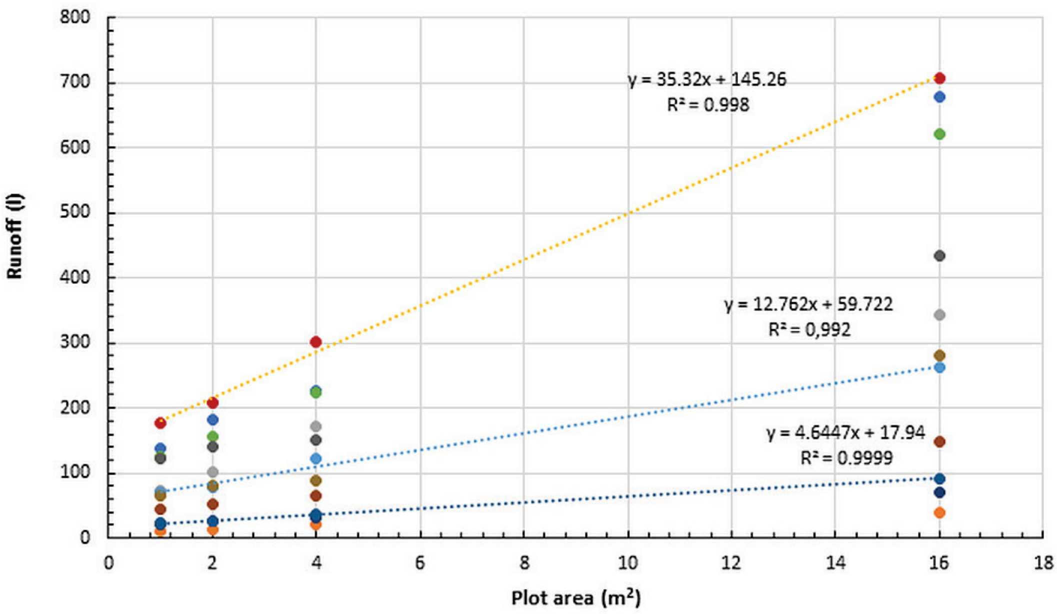

Figure 8. Runoff discharge (%) per year and plot per size of the plots (m^2).

Table 6 also shows that the high magnitude of low-frequency rainfall events is rare. Only 2 out of 470 rainfall days were higher than 100 mm day^{-1}, but they generated most of the runoff. The 9 rainfall events with more than 100 mm contributed 1,291.3 mm of rainfall, and they contribute 458.0, 273.1, 176.4, and 133.6 mm of runoff for the 1, 2, 4, and 16 m^2 plots, respectively. On the contrary, the 416 rainfall events (2,394.2 mm) were registered in rainfall events below 30 mm day^{-1}, contributed with 67.1, 45.46, 34.55, and 17.75 mm of runoff. Table 7 shows the rank of the 20^{th} most intense day and event rainfall event.

Table 7. The rank of the 20 more intense rainfall days and events.

	Day Date	Day mm	Event Date	Event mm
1	28.9.09	140.0	30.9.09	230.0
2	28.2.13	111.0	15.11.12	176.8
3	22.11.11	93.0	9.12.04	167.0
4	28.9.12	90.0	23.11.11	145.5
5	11.11.12	90.0	12.10.07	131.0
6	25.4.13	90.0	11.10.08	119.0
7	26.1.07	80.0	28.2.13	111.0
8	20.3.12	70.0	29.3.04	110.5
9	18.10.07	68.0	25.4.13	100.5
10	11.10.07	67.0	28.9.12	98.0
11	4.12.04	66.0	9.11.06	89.9
12	11.9.06	64.0	14.9.06	88.0
13	12.10.07	64.0	24.3.11	83.5
14	9.10.08	58.0	26.1.07	80.0
15	8.5.08	52.0	30.11.14	72.9
16	8.6.08	52.0	25.4.11	70.0
17	27.9.09	52.0	20.3.12	70.0
18	14.12.09	51.5	29.8.13	70.0
19	28.1.06	50.0	18.10.07	68.0
20	20.10.12	50.0	10.5.08	66.0

Runoff events with over 100 mm event^{-1} contribute with 52.77% of the whole runoff generated along the 11 years of research. This means that 9 runoff events within the 311 measured from 2004 to 2014 control the runoff generation at the agriculture plots in El Teularet study site. Fourteen runoff events generated with total rainfall between 60 and 100 mm event^{-1} contributed with 21.87%. The ones from 30 to 60 mm event^{-1} (39 events) reached 16.97 % and the ones from 10 to 30 mm (107 events) contributed with 8.39 % of the total runoff. This information confirms that few rainfall events are responsible for the runoff yield. González-Hidalgo *et al.,* (2009) informed that the USLE database from the United States Department of Agriculture with 310 plots and 3,195 plot years of data found that 10% of the rainfall events contribute to 50% of the eroded soils. At the El Teularet study site, 1.9% of the rainfall events contribute to 52.77% of the runoff. The importance of the runoff event of high intensity is usually a consequence of specific weather types as Nadal-Romero *et al.* (2014) found. At the study sites Rodrigo Comino *et al.* (2020) found that 60% of the runoff is due to the East winds, the ones from the Mediterranean Sea that contribute to wet and warm air masses. González-Hidalgo *et al.* (2013) used 1800 catchments to be found that the contribution of the suspended sediment load at continental scale was dominated by the 25-largest daily events that delivered 46-63 % of the load, and the 5-largest daily events 23-39 %.

For instance, the mean contribution of the 25-largest daily events varies between 63% and 46% of the total load depending on the basin area, while the mean contribution of just the 5-largest events varies between 39% and 23%. González-Hidalgo *et al.* (2012) used 594 soil erosion plots from the USLE database to demonstrate that soil erosion is a compressed process in time, and that runoff such as has been demonstrated here is generated in few hours along the year. A few numbers of extreme events control the total runoff generated.

In semiarid ecosystems, the concentration of the rainfall results from a contrasted response between rainfall events. López-Bermúdez *et al.* (1998) found that isolated highly intensive rainfall events, mainly in autumns when there is no crop cover, are the main source of runoff and sediments. We found a similar response in El Teularet, where the most efficient rainfall events were found also in autumn such as the one with 140 mm day^{-1} that delivered 9.75 % of the total runoff after 11 years. The research of Romero-Diaz *et al.* (1998) along 9 years of measurements in Murcia (El Ardal research station) and with similar plot sizes (2 x 8 m) found that the wettest years are the ones with the higher runoff discharge and that the main runoff discharge was registered in one thunderstorm also in September (September 29th, 1997) when 86.2 mm contributed with most of the runoff yield.

Tables 6 and 7 show the rainfall and the runoff (for the 4 plots and the total) for the 20 highest largest rainfall events and the values for the 3, 5, and 10 highest rainfall events. The total runoff (mm) generated per plot concentrates on the three most intense rainfall events that yield 9.1 percent of the rainfall but 26 % of the runoff (29.3 % for the plot of 16 m^2). The five largest rainfall events contribute with 37.63 of the runoffs, the 10 highest (22.1 % of the rainfall) reached 54. 46 % of the runoff and the 20 largest rainfall events (34.19 % of the runoff) reached 71.8 % of the runoff. The 310 runoff events are measured in 11 years are concentrated into 10 rainfall events to reach more than one half of the runoff and the three highest rainfall events achieve more than ¼ of the total runoff. Table 8 ranks the runoff events. Table 9 and 10 shows the distribution of the runoff ranks for different rainfall intensities.

Table 8. The rank of the runoff (20 most intense rainfall events) for the four plots and the total discharge (mm).

nº	Runoff Date d/m/y	Rainfall mm Event	Plot 1 1 m^2 (mm)	Plot 2 2 m^2 (mm)	Pot 3 4 m^2 (mm)	Plot 4 16 m^2 (mm)	All plots 23 m^2 (mm)
1	30.9.09	230.0	80.66	49.28	37.61	25.95	193.51
2	15.11.12	176.8	76.60	44.78	24.15	19.39	164.92
3	9.12.04	167.0	65.35	44.77	27.55	22.01	159.69
	3 highest	**573.80**	**222.6**	**138.8**	**89.3**	**67.35**	**518.1**
4	23.11.11	145.5	30.22	18.29	11.42	6.31	66.24
5	12.10.07	131.0	75.56	39.06	27.57	22.83	165.01
	5 highest	**850.3**	**328.38**	**196.20**	**128.30**	**96.49**	**749.36**
6	11.10.08	119.0	41.66	22.84	17.47	9.64	91.61
7	28.2.13	111.0	12.52	8.13	3.65	3.56	27.85
8	29.3.04	110.5	45.33	27.61	16.30	13.38	102.61
9	25.4.13	100.5	30.13	18.29	10.63	10.53	69.58
10	28.9.12	98.0	21.33	11.08	6.65	4.37	43.42
	10 highest	**1389.3**	**479.33**	**284.1**	**183.0**	**138.0**	**1084.4**
11	9.11.06	89.9	34.69	17.85	13.57	6.24	72.34
12	14.9.06	88.0	15.70	12.33	14.25	6.65	48.92
13	24.3.11	83.5	6.99	4.79	2.55	1.35	15.68
14	26.1.07	80.0	24.38	20.16	13.89	8.39	66.81
15	30.11.14	72.9	8.41	4.33	2.56	1.52	16.82
16	25.4.11	70.0	2.55	0.76	0.89	0.53	4.73
17	20.3.12	70.0	14.22	8.13	3.14	1.60	27.08
18	29.8.13	70.0	8.55	4.33	2.40	0.89	16.16
19	18.10.07	68.0	30.25	20.18	11.34	3.74	65.52
20	10.5.08	66.0	5.13	2.72	2.66	0.98	11.49
	20 highest	**2147.60**	**630.17**	**379.72**	**250.24**	**169.86**	**1429.99**

Table 9. The rank of the runoff (20 most intense rainfall events) for the four plots and the total discharge (%).

nº	Runoff Date d.m.y	Plot Surface (%)	Plot 1 1 m^2 (%)	Plot 2 2 m^2 (%)	Pot 3 4 m^2 (%)	Plot 4 16 m^2 (%)	All plots 23 m^2 (%)
1	30.9.09	3.7	9.29	9.24	10.46	11.29	9.72
2	15.11.12	2.8	8.82	8.40	6.71	8.43	8.28
3	9.12.04	2.7	7.52	8.40	7.66	9.57	8.02
	3 highest	**9.1**	**25.63**	**26.03**	**24.83**	**29.30**	**26.02**
4	23.11.11	2.3	3.48	3.43	3.18	2.74	3.33
5	12.10.07	2.1	8.70	7.32	7.66	9.93	8.29
	5 highest	**13.5**	**37.81**	**36.79**	**35.67**	**41.97**	**37.63**
6	11.10.08	1.9	4.80	4.28	4.86	4.19	4.60
7	28.2.13	1.8	1.44	1.52	1.01	1.55	1.40
8	29.3.04	1.8	5.22	5.18	4.53	5.82	5.15
9	25.4.13	1.6	3.47	3.43	2.95	4.58	3.49
10	28.9.12	1.6	2.46	2.08	1.85	1.90	2.18
	10 highest	**22.1**	**55.19**	**53.28**	**50.88**	**60.01**	**54.46**
11	9.11.06	1.4	3.99	3.35	3.77	2.72	3.63
12	14.9.06	1.4	1.81	2.31	3.96	2.89	2.46
13	24.3.11	1.3	0.80	0.90	0.71	0.59	0.79
14	26.1.07	1.3	2.81	3.78	3.86	3.65	3.36
15	30.11.14	1.2	0.97	0.81	0.71	0.66	0.84
16	25.4.11	1.1	0.29	0.14	0.25	0.23	0.24
17	20.3.12	1.1	1.64	1.52	0.87	0.70	1.36
18	29.8.13	1.1	0.98	0.81	0.67	0.39	0.81
19	18.10.07	1.1	3.48	3.78	3.15	1.63	3.29
20	10.5.08	1.1	0.59	0.51	0.74	0.43	0.58
	20 highest	**34.19**	**72.56**	**71.20**	**69.57**	**73.88**	**71.81**

Table 10. Distribution of the runoff discharge per rainfall events.

Plot Surface	Plot 1 1 m² (l)	Plot 2 2 m² (l)	Pot 3 4 m² (l)	Plot 4 16 m² (l)	All plots 23 m² (l)
>100	458.00	273.07	176.35	133.60	**All plots**
>60	197.96	121.83	85.01	41.82	446.62
>30	145.41	92.98	63.77	36.73	338.90
>10	67.10	45.46	34.55	17.75	164.85
>5	0	0	0	0	0
>0	0	0	0	0	0
Total	868.47	533.34	359.68	229.90	1991.39

Plot Surface	Plot 1 1 m² (%)	Plot 2 2 m² (%)	Pot 3 4 m² (%)	Plot 4 16 m² (%)	Total 23 m² (%)
>100	52.74	51.20	49.03	58.11	52.28
>60	22.79	22.84	23.63	18.19	22.43
>30	16.74	17.43	17.73	15.98	17.02
>10	7.73	8.52	9.61	7.72	8.28
>5	0	0	0	0	0
>0	0	0	0	0	0
Total	100.00	100.00	100.00	100.00	100.00

3.4. Runoff generation and connectivity

The results of the 11 years of measurements at El Teularet research station demonstrate that the runoff at the plot scale (from 1 to 16 m^2) is highly determined by the size of the plot. As larger is the plot lower is the runoff discharge per unit, suggesting that the average duration of the runoff event –after the soil becomes saturated till the end of the rainfall event plus the duration of runoff-flow after ending precipitation– depends on the drainage area (López-Vicente and Navas, 2012). Another key information delivered in this research is that after 311 runoff events at the plot scale, 160 resulted in effective runoff at the plot scale, but only 1 delivered runoff to the stream (Barranco de Benacancil). A concept that can help to understand the hydrological behavior of the dry (ephemeral) rivers in the Mediterranean is the connectivity concept, as the loss of the overland flow discharge is due to how the flows are connected. The right term to be used under the Mediterranean karstic hydrological system is Dis-Connectivity, as it is rare that the runoff generated at pedon and slope scale will reach the stream. The use of the connectivity concept can help for the understanding of the geomorphic systems and the hydrological cycle in the continents (Bracken and Croke, 2007; Masselink *et al*., 2017).

The connectivity of the flows explains also the sediment reallocation along slopes and watersheds and affects the distribution of the vegetation (Keesstra *et al.,* 2018; Gerenmew and Triest, 2019). In El Teularet, the tilled plots induce higher connectivity than a forest due to the lack of vegetation that reduces the connectivity of the flows, and because agricultural land is better connected than the forest ones due to the high density of roads, drainages, and bare soil surfaces (Keesstra *et al.*, 2019). The smoothed topography of the agricultural land also contributes to high connectivity (Yu and Harbour, 2019) than can be only reduced by the ridges such as Rodrigo-Comino *et al.* (2018a) found in agricultural land cultivated with vineyards. The connectivity concept can also be used to investigate degradation thresholds in arid and semiarid ecosystems such as Saco *et al.* (2020) did.

In El Teularet experiment carried out along 11 years the connectivity of the flows was zero below 10 mm day^{-1} of rainfall following the measurements carried out on the four plots. Rainfall events higher than 10 mm day^{-1} contribute to runoff, and the discharge was higher as higher was the runoff. The largest runoff discharges were measured during the high rainfall events. We also demonstrated that the connectivity of the flows is determined by the length of the plots because as larger the plot lower the runoff discharge per unit area.

When the slope length increases, there is a reduction in the runoff discharge per unit area due to the loss of runoff as a consequence of the ponding developed as a consequence of the roughness of the tillage (Zhao *et al.,* 2018; Luo *et al.,* 2020). The loss of surface flow due to infiltration of runoff due to macropores (cracks or fauna and plant macropores) and due to the increase in the infiltration as the pressure of the ponds also explain that the runoff is reduced with the size of the plots (Cerdà and Rodrigo-Comino, 2020; Jourgholami and Labelle, 2020). The runoff coefficient in small plots increases more with increasing storm size than in large plots (Fig. 9 and 10). When this trend is extrapolated to the watershed it is found that only extreme events will generate hortonian overland flow that will reach the valley bottom and will create a flood event in the channel network, but this only took place along the study period once in eleven years.

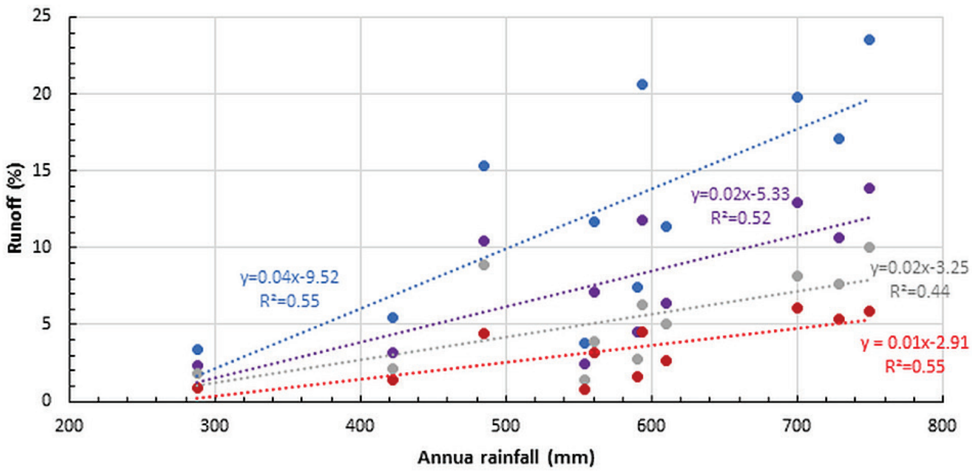

Figure 9. Runoff discharge (l) per year and plot per size of the plots (m²).

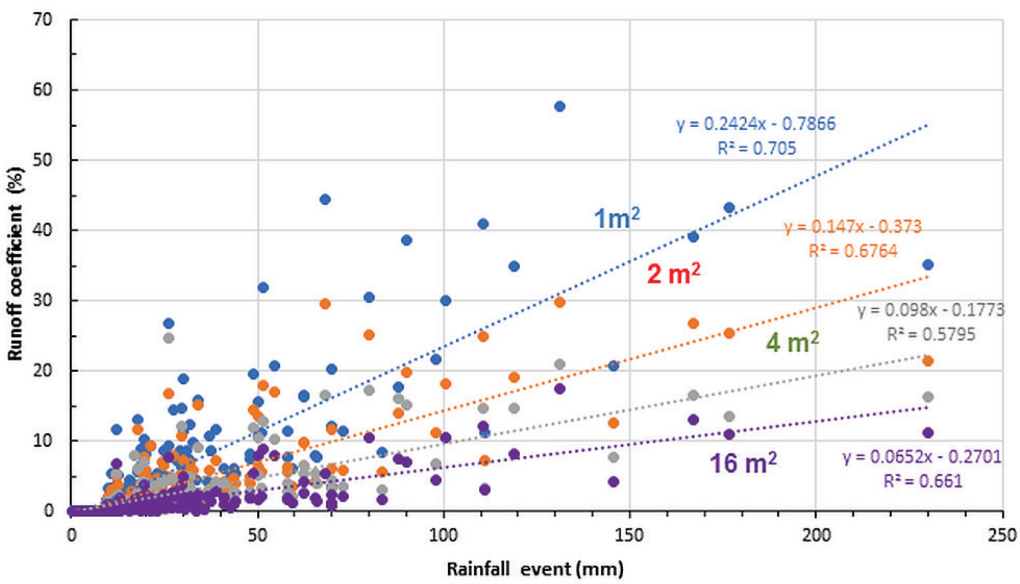

Figure 10. Relationship of annual rainfall on runoff discharge for the four plots (1, 2, 4, and 16 m²) from 2004 till 2014.

In other studies, it was identified that under Mediterranean climatic conditions the hydrological system is disconnected from the stream network (Masselink *et al.,* 2017). And the runoff in the channel used to originates from close areas to the channel network or from roads and degraded areas near the talweg. The contribution of the throughflow or groundwater flow at the study site is negligible due to the karstic system that allows the infiltrated water to deeply percolate in the aquifer. This behavior was found also on vineyards where the tillage induces the formation of ridges underneath the vines and reduces the runoff generated and the connectivity of the flows (Rodrigo-Comino *et al.,* 2018b) that only new plantations increase the flows.

During large events, the hydrological system becomes connected through overland flow, which is mainly hortonian overland flow, but this is very rare in the study area due to the low connectivity of the flows such as show the influence of the length of the plot. During these events also sediment is transported to the channel network, which means that the hydrological system also dis-connects the sediment transport system that is only active for a few days or even hours. This is relevant on agricultural land where soil erosion is very active due to the degradation of the soil organic matter and where land abandonment is relevant (Lasanta *et al.,* 2019). The runoff generated in the slopes is highly dependent on the weather types such as Rodrigo-Comino *et al.* (2020) demonstrated. Recently, approaches to show the spatio-temporal changes of floods generation confirms the relevance of the runoff generated at pedon and slope scale (Contreras *et al.,* 2021), and snow is relevant on mountainous areas (Pisabarro, 2020) and were the runoff connectivity and soil losses are encouraged by the trails (Salesa and Cerdà, 2019).

In the case of the study at hand, the dis-connectivity is an extreme case due to the local conditions. The limestone (karst) induces high percolation, the marly areas devoted to agriculture land are located in some patches that also show low connectivity within the slope and negligible with the river. The connection between the runoff producing hillslopes and the channel network is only established during an extreme event, such as the one measured in September 2009.

4. Conclusions

Eleven years of measurements employing plots of different sizes (1 to 16 m^2) and an assessment of the floods in the stream allow us to conclude that there is very deficient connectivity between the slope and the streams. Within the slope under tillage recurrent runoff events (160 in 11 years) were measured, but the runoff discharge is disconnected with the stream (1 runoff event in 11 years). The concentration of the runoff in a few rainfall events also contributes to the lack of connectivity in most of the rainfall events. The three most intense rainfall events contributed to 26 % of the runoff in 11 years. Ten rainfall events contributed to 55 % of the runoff at the plot scale. A 140 mm day^{-1} rainfall event connected the runoff from the plots to the Barranco de Benacancil creek. No other rainfall event contributed to a flood at a watershed scale.

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FLASH-FLOODING OF EPHEMERAL STREAMS IN THE CONTEXT OF CLIMATE CHANGE

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ABSTRACT. Ephemeral streams, which are more extended than expected, entail a significant flood risk. Historically they have been underestimated due to their intermittent flow and the lack of knowledge on their hydro-geomorphology. Currently, European legislation recognizes their associated risk and supports research into them, adapting the scale and methodology to their characteristics. Based on the compilation of various works carried out in four Valencian catchments (Eastern Spain), this paper approaches the key questions of rainfall-runoff conversion and flood generation in ephemeral streams, taking into account their hydro-geomorphological specificity. Moreover, the consequences which derive from current environmental changes are addressed in the wider scale of Júcar River Water Authority.

The study is based on 5-minute data, registered by the SAIH-Júcar network (Authomatic Hydrological Information System). The investigation has been conducted in two phases. Firstly, key issues determining flash-flood generation at basin scale have been addressed, based on the study of 138 floods, registered between 1989 and 2018, in four Valencian ephemeral streams (Barranc del Carraixet, Rambla de Poyo, Riu Vernissa and Rambla de Gallinera). Secondly, concerning a broader scale (Júcar River Water Authority), the evolution of 698 rain episodes (1989-2007) has been analysed. Finally, the consequences that environmental changes (climatic, anthropogenic and morphogenetic) might mean for flash-flood generation have been discussed.

The results show how environmental changes point towards an increase in risk to the detriment of resource. Rain episodes tend to increase in intensity and decrease accumulated precipitation. As a consequence, hydrological connectivity will become more dependent on rain intensity, thus reducing runoff thresholds and basin response times. Anthropic changes enhance this behaviour, reducing infiltration and increasing surface runoff and erosion, while accelerating the hydrological cycle. An increase in process-form disequilibrium in Mediterranean catchments can be expected due to the increase in morphogenetic phases (because of the intensification of events) and a decrease in the efficiency of low-magnitude recovery episodes.

Consequently, the behaviour of ephemeral-streams under current climate change conditions points firstly to an increase in intense flash-flood events, which will be difficult to manage with the current flood control measures, and secondly an increase in the general aridity conditions of catchments.

Las avenidas súbitas en ramblas en un contexto de cambio climático

RESUMEN. Las ramblas mediterráneas, más extendidas espacialmente de lo que pudiera parecer, implican un riesgo de inundación significativo, históricamente subestimado debido a su flujo intermitente y al desconocimiento generalizado sobre su funcionamiento hidrogeomorfológico. Actualmente, sin embargo, la legislación europea reconoce la especificidad de estos sistemas, así como el riesgo que entrañan y aboga por profundizar en su conocimiento, adaptando la escala y la metodología a sus particularidades. Basado en la recopilación de varios trabajos realizados sobre la zona de estudio, el presente artículo aborda cuestiones clave de la conversión lluvia-caudal y generación de crecidas en ramblas, así como su evolución en el contexto actual de cambio ambiental.

El estudio se basa en datos originales cincominutales, registrados por la red SAIH-Júcar (Sistema de información hidrológica automática) y se realizó en dos fases. En primer lugar, se abordaron cuestiones clave que determinan la generación de crecidas a escala de cuenca, a partir de 138 eventos, registrados entre 1989 y 2018, en cuatro ramblas valencianas (Barranc del Carraixet, Rambla de Poyo, Riu Vernissa y Rambla de Gallinera). En segundo lugar, a una escala más general, se ha analizado la evolución de 698 episodios de lluvia en el territorio de la Demarcación Hidrográfica del Júcar, entre 1989 y 2016, con objeto de inferir qué consecuencias podrían suponer los cambios ambientales para la formación de inundaciones en ramblas. Los resultados muestran cómo estos cambios sugieren aumento del riesgo y disminución del recurso. Los episodios tienden a aumentar su intensidad y a disminuir la precipitación acumulada. Como consecuencia, la conectividad hidrológica se vuelve cada vez más dependiente de la intensidad de la lluvia, reduciendo así los umbrales de escorrentía y los tiempos de respuesta de la cuenca. Los cambios antrópicos potencian este efecto, porque reducen la infiltración y aumentan la escorrentía superficial y la erosión, al tiempo que aceleran el ciclo hidrológico. Por tanto, se anuncia un aumento en el desequilibrio proceso-forma debido al aumento de las fases morfogenéticas (por intensificación de los eventos) y a una disminución en la eficiencia de los episodios restauradores de baja magnitud. En consecuencia, el comportamiento de las ramblas bajo condiciones de cambio climático apunta, en primer lugar, hacia un incremento de las flash-floods intensas, cada vez más difíciles de gestionar con los instrumentos habituales de control de avenidas y, en segundo lugar, hacia una progresiva aridificación de estas cuencas mediterráneas.

Key words: intermittent rivers, environmental change, Mediterranean, inundation, risk.

Palabras clave: ríos intermitentes, cambio ambiental, Mediterráneo, inundación, riesgo.

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1. Introduction

Ephemeral streams are more frequent than assumed since, globally, more than 50% of the river network is intermittent (Skoulikidis *et al.,* 2017). In the case of Europe, the Mediterranean strip is the most affected, with percentages that can vary from 20% in the case of France (Snelder, 2013) to more than 90% in Sardinia and Sicily (Petrakis *et al.,* 2012). Gómez *et al.* (2005) estimate that more than 70% of fluvial systems are ephemeral streams in the south-east of Spain. An increase in this percentage is to be expected over the next century, because as a consequence of climate change, drylands are predicted to expand approximately by 10% before the 22nd century (Feng and Fu, 2013).

In the Mediterranean region, ephemeral streams exhibit certain climatic, geomorphological and anthropic characteristics which condition the hydro-geomorphological processes of runoff generation. Climatically, seasonal rainfall regime is very irregular as it is subject to severe summer droughts and autumn episodes of high intensity (Camarasa-Belmonte and Soriano, 2014). From the geomorphological point of view, basins are small and steep with permeable lithology and wide channels (hydrologically disconnected from the aquifers). Headwater used to be covered by species adapted to water stress and poorly developed soils (Gómez *et al.,* 2005). However, floodplains are very fertile and have suffered from intense human occupation for over 8000 years (Butzer, 2005). Regardless, the Mediterranean environment, often described as highly degraded, has been able to develop strong ecological and human resilience to degradation (Butzer, 2005).

However, the current important changes, both environmental and anthropic, are threatening the precarious balance between water resources and flood risk (Barredo and Engelen, 2010; Durán *et al.,* 2014; Camarasa *et al.,* 2020). On the one hand, climate change on a global scale has accelerated the hydrological cycle with the result that episodes of catastrophic floods have increased and intensified (Olcina *et al.,* 2017). On a regional scale, according to all indicators (European Environment Agency, 2019), the Mediterranean region will suffer the greatest impact in Europe, since it is a transitional area which is more exposed to extreme events. On the other hand, on a basin scale, changes in land use are affecting the ephemeral stream environments, in particular due to the degradation of headwaters as well as the indiscriminate occupation of floodplains (Canton *et al.,* 2011; Calsamiglia *et al.,* 2018). Flood risk is exponentially increasing but, paradoxically, this fact is being underestimated because of the intermittence of flow.

The estimation and adaptation to flood risk in ephemeral streams, under a context of climate change, goes through two phases: firstly, understanding and recognizing the specificity of Mediterranean hydrology (as a morphoclimatic transition between humid and arid environments) and secondly, analyzing what may be the reaction of these fluvial systems to the evolution of intense rainfall episodes.

The first part requires focusing the analysis on empirical flash flood case studies (Shannon *et al.,* 2002), which is not easy given the lack of sufficient and detailed hydrological information (Zoccatelli *et al.,* 2019). The lack of flow data is partly due to the low economic interest that ephemeral streams have long generated. Precisely due to their intermittency they have not been considered as a water resource. Furthermore, even in the case of the availability of information, data were of poor quality and not sufficiently detailed regarding flash-flood times. The information was generally recorded every day, whereas a sub-daily time scale (hourly or even minute scale) was needed in order not to mask the processes (Camarasa-Belmonte, 2016).

However, this situation regarding the lack of knowledge has begun to change. This change has been driven by the European legislative framework (EU Floods Directive2007/60/EC), which recognizes the significant risk caused by flash-floods generated in intermittent Mediterranean ephemeral streams. Thus, the hydrological specificity of these fluvial systems is highlighted, as well as the need for developing methodology and to adjust data set to small catchment scale. In this sense, it is worth noting the effort made in recent years by the scientific community to analyse cases of flash flooding and associated risks. The second part, related to the evolution of these floods under the climate change conditions, is currently crucial for Spain because, as stated in the report on Floods and Climate Change prepared by the Ministry for Ecology Transition (2018), "an increase in flash floods in most of the basins in Spain has been observed" (MINECO, 2018).

The present study addresses both phases: that of flash flood generation, and its trend under the current context of climate change in a wide area of the Spanish Mediterranean coast. This paper is based on previous studies carried out in the territory of Jucar River Authority from detailed data provided every five minutes by the Automatic Hydrological Information System (SAIH) network. The investigation was conducted in two phases and addressed two work scales.

The first part of the study approaches the key issues of flash-flood generation in ephemeral streams, based on the analysis of 138 events registered in four gauged pilot sub-basins (ranging from 25 to 185 km^2) from 1989 to 2018. During the second phase, a more general scale of study has been addressed, concerning the entire territory of Jucar Water Authority (42,989 km^2). Climate, anthropic and geomorphic changes have been described in order to analyse how trends in environmental changes can affect flash-floods. In summary, this research aims to provide a dynamic framework to integrate both scales, those of basin and climate, as well as their interaction under conditions of environmental change.

2. Study area

The study area involves two spatial scales: (i) the basin scale, to study flood hydrology processes in ephemeral streams, and (ii) a more general scale, to frame the evolution of environmental changes (Fig. 1).

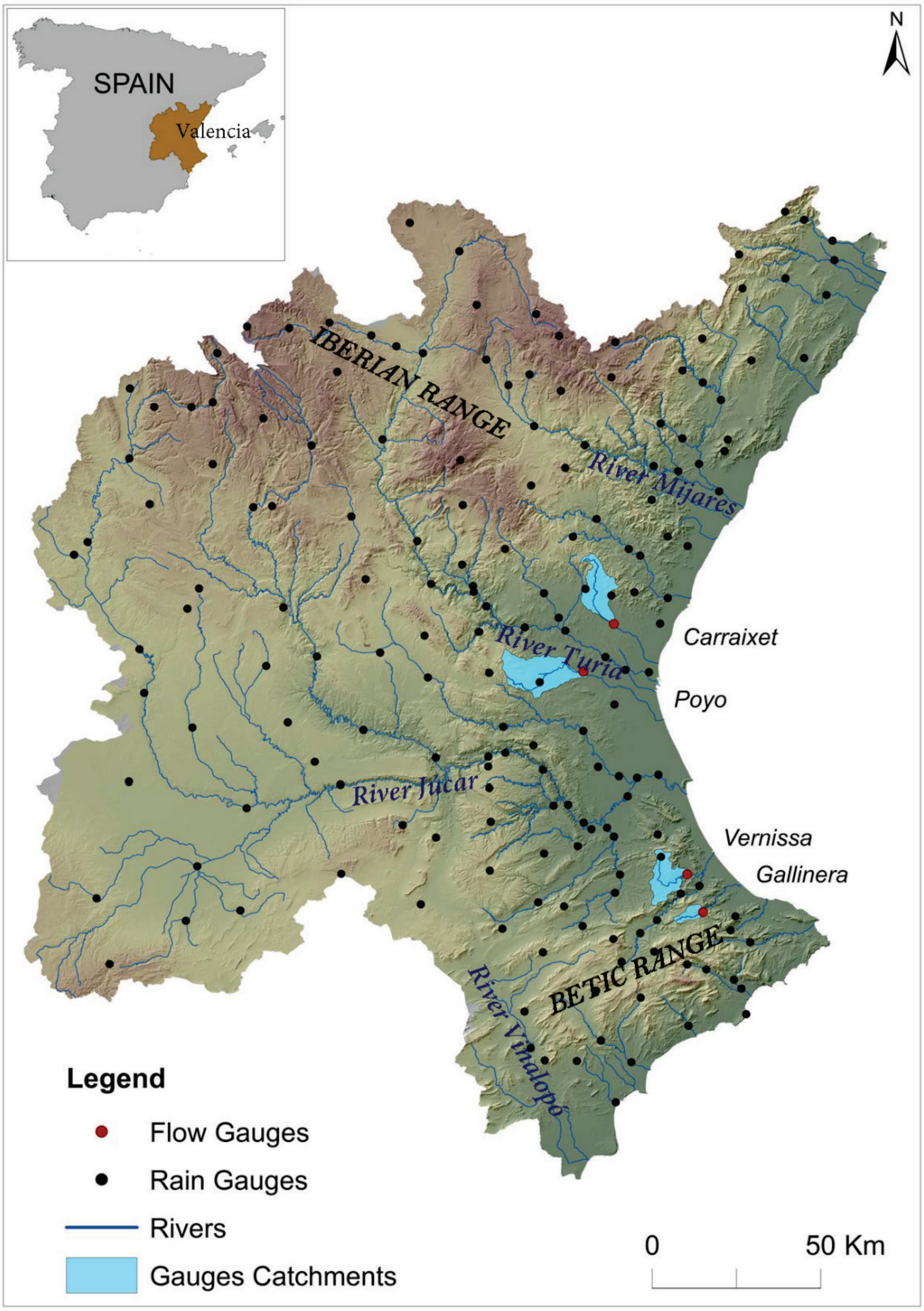


Figure 1. Study area.

The basin scale includes four Valencian ephemeral streams, monitored by the SAIH network. The hydrological analysis was carried out in the gauged sub-basins of the following watersheds: Barranc del Carraixet; Rambla de Poyo; Rambla de Gallinera and Riu Vernissa, whose main characteristics are listed in Table 1. Areas range from 27 Km^2 in Gallinera (gauged at headwater) to 187 km^2 in Poyo. Slope of catchments is high, varying from 33% in Gallinera to 17% in Poyo. Runoff thresholds, also known as initial abstraction, have been calculated from the physical features of the basin according to the SCS method (1972), which was adapted to Spain by Témez (1978). The average threshold for pilot catchments is 64 mm (from 56 to 72 mm).

Table 1. Gauged sub-basins features.

Catchment	Surface (km^2)	Slope (%)	Initial abstraction (mm)
Carraixet	125	21	70.8
Poyo	185	17	57.8
Gallinera	27	33	56.6
Vernissa	102	25	72

The broader scale involves the territory of Júcar Water Authority (42,989 km^2), in the east of Spain. The climate is typical Mediterranean, with 500 mm of average annual precipitation (from 800 mm in the north to 300 mm in the south). Intense rainfall episodes concentrate in autumn-winter and spring.

The study area is quite heterogeneous and shows a marked inland-coast dichotomy. Inland is mountainous and includes the headwaters whereas on the coast, flood-plain and other sedimentary forms have been developed. Regarding extreme episode distribution, intense rainfall in the littoral is five times higher than inland (Morrell and Pérez-Cueva, 2000). Camarasa-Belmonte and Soriano (2014), using 5-min detailed data, checked that higher rainfall intensities were registered close to the sea, whereas lower rainfall intensities affected the inland area. From a human perspective, water resources are generated and stored inland (where dams and broad aquifers are located) while flood risks are expected on the coast (where larger urban centres are placed).

3. Methods and materials

Several studies of both topics, the generation of floods in ephemeral streams (Camarasa-Belmonte, 2016) and trends in rain episodes (Estrela *et al.*, 2016; Marcos-García and Pulido-Velázquez, 2017; Camarasa-Belmonte *et al.,* 2020), have been carried out in the study area. This paper combines the main results previously obtained by Camarasa-Belmonte with new analysis of recent episodes to illustrate the key issues of flash-floods. The aim is to discuss how ephemeral streams could behave under the current trend in climate change.

Original data were recorded by the SAIH network every five minutes from 147 rain gauges and 4 streamflow (one in each pilot catchment) between 1989 and 2018. For the hydrological study at catchment scale, 137 flash-flood events were analysed (16 in Carraixet, 38 in Poyo, 38 in Gallinera and 45 in Vernissa) between 1989 and 2007 (Camarasa-Belmonte, 2016). A multi-peak flood event (October 2018 in Vernissa) has been added to the study. The events were selected because the data were reliably collected and they covered a representative range of floods including the most damaging.

The following hydrological indicators have been estimated for each flood event (using data provided by 16 rain-gauges and 4 stream-gauges, which covered sub-basins):

a) Spatial averaged rainfall inputs (Thiessen polygons were used to average point data):

   – Hyetograph of areal intensity (mm/h).

- Accumulated areal rainfall during the event (mm)

b) Water balance:

- Runoff threshold (P_o) (mm): amount of precipitation needed to generate runoff, empirically estimated for each event, from Curve Number method (SCS, 1972), adapted to Spain by Témez (1978).
- Runoff coefficient (%): discharge as a percentage of total precipitation.
- Runoff deficit (mm or hm^3): The difference between precipitation and flow discharge.

c) Discharge:

- Flood volume (mm or hm^3)
- Peak flow (m^3/s) and specific peak flow ($l/s/km^2$)

Regarding the study of rainfall episode trend at the broader scale of River Júcar Water Authority, results obtained by Camarasa-Belmonte *et al.* (2020) have been used. According to this paper, 698 rainfall episodes were selected (1989-2016), following the criteria proposed by Camarasa and López-García (2006). The authors developed a method, based on thresholds of daily accumulated rainfall and intensity, to detect *hydrologically significant episodes*, that is, those episodes able to generate runoff, at least in a part of the basin. Selected episodes were characterised by indicators of accumulated precipitation, maximum intensity, reduced averaged intensity and persistence. These indicators were defined in the following way:

i. Accumulated precipitation: spatial mean accumulated rainfall in the episode.
ii. Maximum instantaneous intensity: absolute maximum 5-min intensity, registered in any of the gauges.
iii. Reduced average intensity: spatial averaged intensity (considering only the intervals with rainfall in each rain-gauge).
iv. Persistence: spatial mean of the persistence, that is, the probability of rain occurring during two consecutive 5-min intervals.

Taking into account these characteristics, rainfall episodes were classified by a cluster analysis into three types. Trends in frequency, accumulated rainfall and intensity were estimated for all of events and for each type of episode (Camarasa-Belmonte *et al.,* 2020). From a geomorphic point of view, efficiency of episodes was estimated by dividing the water contribution with the number of episodes. Distinction between inland and coast episode trend were also traced.

4. Results and discussion

4.1. Floods in ephemeral-streams: key issues

Mediterranean environments, located between humid and arid climates, show an intermediate semi-arid hydrological behaviour dominated by extreme events (Brakenridge, 1988, Bracken and Crocke, 2007). Hydrological processes and flood generation in ephemeral-streams are conditioned by two key issues: the intermittence of flow and the magnitude of rainfall episode. On the one hand, most of the year the channels remain dry because they are hydrologically disconnected from the aquifer. On the other, as the discharge depends almost exclusively on the rainfall, floods are determined by the episode characteristics.

4.1.1. Hydrological connectivity and intermittence of flow

Ephemeral streams show two factors of discontinuity: (1) the basin geomorphological configuration, which favours surface flow transfers to groundwater and, (2) the storm spatio-temporal variability. Bracken and Croke (2007) described *static connectivity*, referring to spatial patterns (physical features of catchment) and *dynamic connectivity*, referring to long-term landscape evolution, as well as variations in inputs of rainfall. Therefore, the intermittence of water flow can be addressed from both spatial and temporal points of view.

From a spatial perspective, hydrological connectivity, at a detailed scale, depends on the connection between patches with different hydrological soil behaviour (Yair and Kossovsky, 2002; Bracken and Croke, 2007; Wainwright *et al.,* 2011; Bracken *et al.,* 2013). Thus, local heterogeneity of the territory can cause discontinuity in runoff (Cammerat, 2004; Canton *et al.,* 2011).

Additionally, at basin scale, hydrological connectivity can be interrupted because runoff becomes re-infiltrated in certain sectors of the basin. The geomorphological configuration of ephemeral streams is used to show three main sectors (Camarasa-Belmonte, 2016): (i) the steep headwaters sector; (ii) an intermediate sector, which connects headwaters to alluvial plain, where slope suddenly decreases and transitional sedimentary forms (alluvial fans, glacis, piedmonts) are developed, and (iii) the floodplain. Hydrologically, headwaters produce runoff quickly, but flow can be reabsorbed (run-on) at intermediate sectors by the permeable sedimentary forms. Streambank morphology and coarse texture of dry channels also decrease direct flow because they favour transmission losses to groundwater (Bull, 1997; Beven, 2002; Bull and Kirdby, 2002; Costa *et al.,* 2013; Segura-Beltran and Sanchis-Ibor, 2013; Zoccatelli *et al.,* 2019).

From a time perspective, direct runoff depends almost entirely on rainfall events. As a consequence, these systems remain dry most of the year. However, the mere occurrence of a rain episode does not guarantee the connectivity of the basin. Only events of certain magnitude ensure the flow reaches the outlet. The influence of antecedent soil moisture is relevant to the catchment connectivity (Yair and Kossovsky, 2002; Borga *et al.,* 2014; Zoccatelli *et al.,* 2019). Thus, both soil water reserve (on a monthly scale) and catchment moisture on an event scale (considering rain from the 5 days before the episode) should be taken into account.

Figure 2 illustrates these questions related to intermittency of flow by comparing two multi-peak floods which were registered at Vernissa catchment in October 2018 (16-20) and December 2004 (3-16). Both hydrographs exhibit the strong dependence on the rainfall structure. The main difference between them derives from the intermittency of flow in October 2018 compared to the continuity of flow in December 2004. The reason for this is the total accumulated precipitation during the episode (since the intensity is similar) and water resources stored in the system since the summer. In both cases the antecedent moisture condition was dry (AMC 1).

In the October 2018 event 82 mm of accumulated rainfall was recorded, while in December 2004 precipitation reached 376 mm (Table 2). Furthermore, in December 2004 the basin had received 96 mm from the summer, whereas in October 2018 this was only 79 mm. Therefore, the water stored in the catchment was greater in December 2004 than in October 2018. Thus, during a December 2004 event a base-flow of 10 m^3/s was generated. Although in both events peaks of the hydrograph reproduce the rainfall structure, the accumulated and persistent precipitation of December 2004 makes the hydrological connectivity possible, similar to those of perennial fluvial systems.

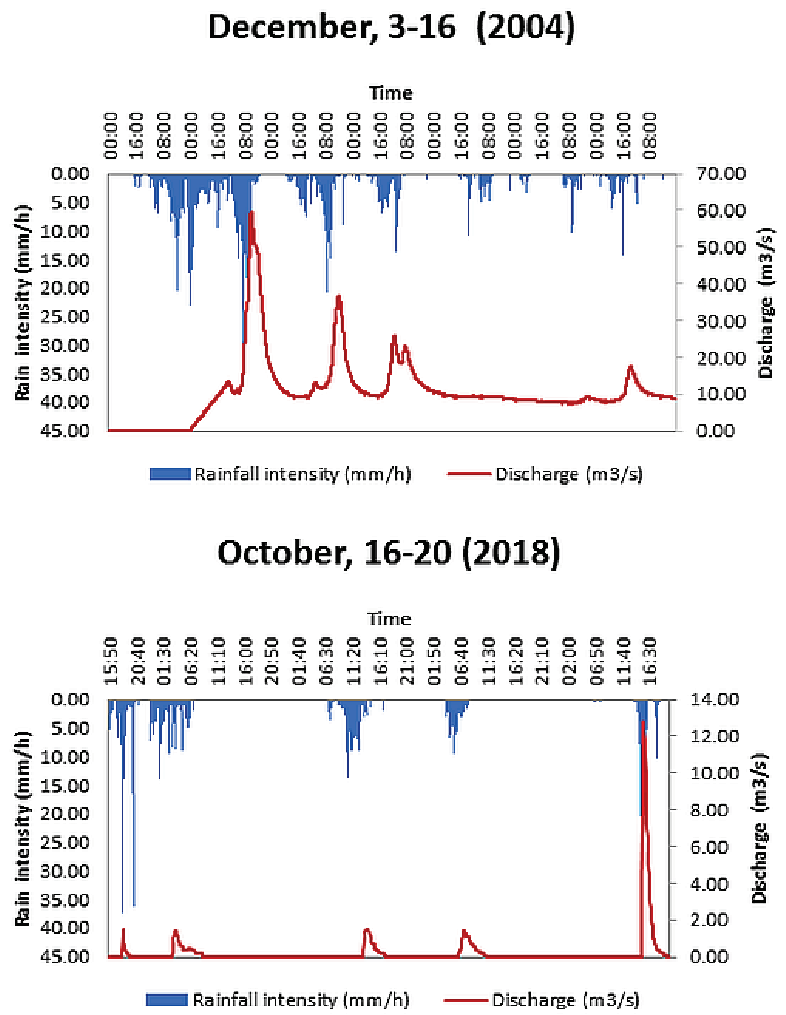


Figure 2. Comparison between two multi-peak floods registered at Vernissa catchment.

Table 2. General hydrological characteristics of multipeak floods registered at Vernissa basin (December 2004 and October 2018).

Event	Accum. rain (mm)	Absolu. max. intensity (mm/h)	Averag. max. intensity (mm/h)	Flood volume (hm^3)	Runoff coeff. (%)	Runoff deficit (hm^3)	Runoff threshold (mm)	Maximum peak-flow (m^3/s)
December 2004	376	57	33	8.87	22	31	72	60
October 2018	82	139	37	0.08	1	8	10	13

4.1.2. Magnitude of episodes: the importance of single events

One of the most important nonlinearity factors for hydrological connectivity is linked to storms: magnitude, spatial location (Zoccatelli *et al.,* 2011) and temporal evolution (Camarasa-Belmonte, 2016).

As mentioned, flood events are due to single rainfall episodes which are large enough to generate direct quick-flow. Thus, approaching flood analysis from monthly or annual averaged rainfall data makes no sense in the Mediterranean environment, since it is dominated by extreme events (Graff, 1988; Camarasa-Belmonte and Soriano, 2014; Borga *et al.,* 2008). On the contrary, in these basins the study should be focussed on single specific episodes of a certain magnitude, registered at a detailed scale (Zoccatelli, 2011; Zoccatelli *et al.,* 2019).

Yair and Raz-Yassif (2004) carried out a study in the Negev Desert (Israel) concerning runoff generation at different scales and concluded that only high episodes guaranteed the hydrological connectivity at basin scale. The importance of high magnitude events has been corroborated by, among others, Bull *et al.* (1999), López-Bermúdez *et al.* (2002) and Cammeraat (2004), when looking at catchments in southeast Spain.

The question is how to define what high magnitude episode means for a Mediterranean environment and which rainfall indicators should be used. Camarasa-Belmonte (2016) revealed how episodes, which are considered of high magnitude in relation to both indicators, accumulated rainfall and intensity, could generate runoff, floods and inundations. According to this author, accumulated rainfall influenced water balance, hydrograph volume and peak-flow, while intensity conditioned the speed of processes and the time of basin response.

4.1.2.1. Large episodes regarding accumulated rainfall: the influence on water balance and discharge peaks

Accumulated rainfall is a crucial indicator of an episode's magnitude in semi-arid environments (Yair and Raz-Yassif, 2004; Bracken *et al.,* 2008). Zoccatelli *et al.* (2019) analysed rainfall-runoff processes at catchment scale in 13 ephemeral streams located in the eastern Mediterranean region. They concluded that rainfall depth and antecedent conditions were the most important properties to flood response. Similar results were obtained in south-east Spain (Bull *et al.,* 1999; Conesa, 2005; Bracken *et al.,* 2008).

Regarding Valencian ephemeral streams, Camarasa-Belmonte (2016) confirmed the influence of accumulated rainfall on water balance parameters (runoff threshold, runoff coefficient and runoff deficit), with runoff deficit being the most strongly correlated indicator. Thus, basin storage processes are favoured by large magnitude episodes. The flood volume and the peak flow are also significantly conditioned by accumulated rainfall. Figure 3 and Table 3 show these dependence relationships.

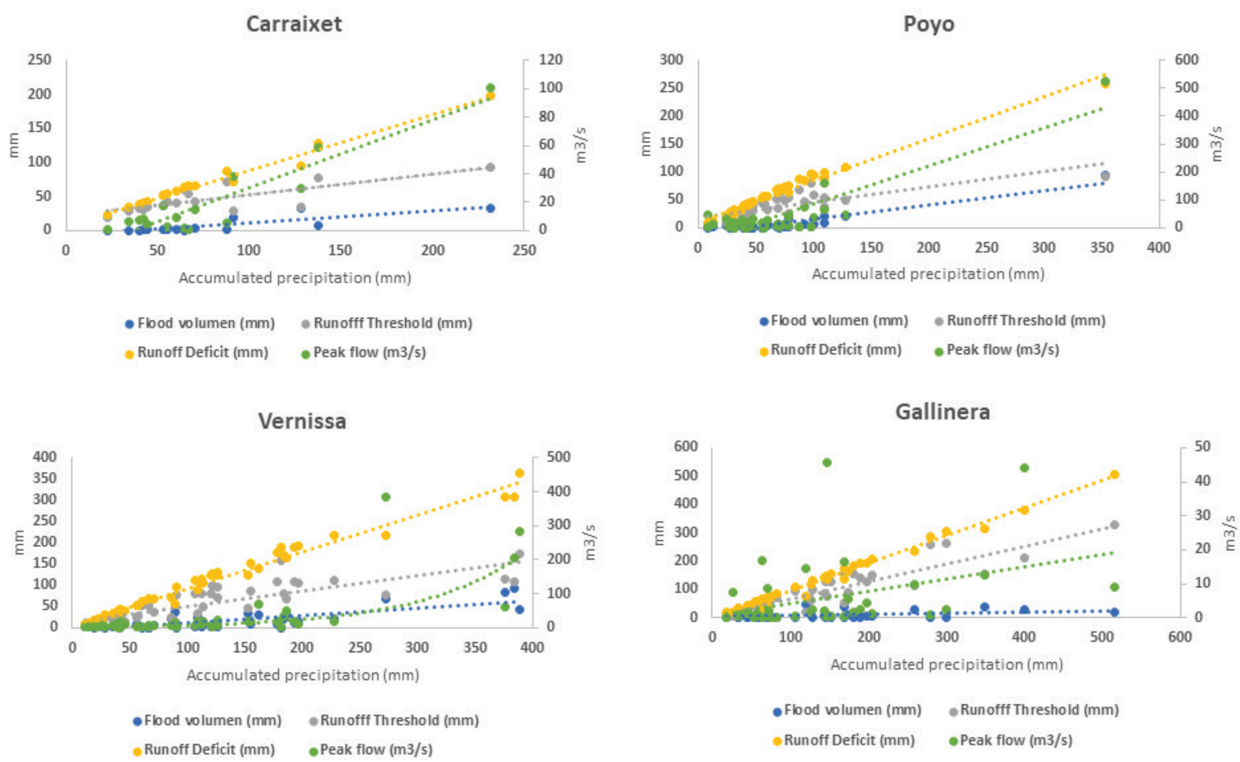


Figure 3. Influence of accumulated rainfall on water balance parameters and peak flow.

Table 3. Correlation (r^2) between accumulated precipitation and flood indicators.

BASIN	Water Balance Indicators		Discharge indicators	
	Runoff thresholds	Runoff Deficit	Flood volume	Peak flow
Carraixet	0.61	0.98	0.69	0.86
Poyo	0.57	0.97	0.83	0.78
Vernissa	0.67	0.97	0.65	0.61
Gallinera	0.81	0.98	0.12	0.14

Despite all basins having the same trend, the relationships were particular for each catchment, according to their physical characteristics. For example, in Gallinera, the influence of rainfall on discharge indicators was very low because the dataset was registered in headwaters. The gauged sub-basin is small and permeable showing considerable run-on processes at the slope base.

Figure 2 also shows this behaviour in Vernissa basin, comparing floods of October 2018 and December 2004. Although the systems remained drier in October 2018 than in December 2004, runoff threshold in October is 10 mm while in December it is 72 mm. Also, runoff deficit is higher in December (31 hm^3) than in October (8 hm^3) because of the accumulated rainfall.

Generally, only 6% of rainfall is converted to runoff (from runoff thresholds around 62 mm), in Valencian ephemeral streams (Camarasa-Belmonte, 2016). However, in large episodes values multiply, especially concerning small and permeable catchments (Table 4). The event of October 2000 is an example for all the basins. Gallinera is very representative because during the event it showed a runoff threshold of 327 mm, whose value when averaged is 92 mm.

Table 4. Comparison between averaged and extreme values (October 2000 event) of accumulated rainfall and water balance indicators.

Basin	Accumulated precipitation (mm)		Runoff threshold. P_0 (mm)		Runoff deficit (mm)		Runoff Coefficient (%)	
	Averaged	October 2000 event	Averaged	October 2000 event	Averaged	October 2000 event	Averaged	October 2000 event
Carraixet	76.81	231.73	45.41	92.8	70.13	198.64	5.25	25
Poyo	62.96	353.42	35.74	91.92	50.08	258.81	6.47	27
Gallinera	142	514.79	92.8	327.05	135.26	505.7	7.74	56
Vernissa	116.95	389.34	57.68	174.41	107.79	363.8	10.71	42
Average	99.53	344.87	62.7	172.5	93.61	311.56	6.31	31

In summary, high magnitude episodes (in terms of accumulated rainfall) show ambivalence towards resource and risk. On the one hand, they are the main water resource for semi-arid environments because they provide slope runoff and channel flow in addition to transferring water to the aquifer and other basin storage forms. They ensure the hydrological connectivity by making the behaviour of humid and Mediterranean fluvial systems act in a more similar way. On the other hand, they produce large discharges and peak-flows, generating important flood.

4.1.2.2. Intense episodes: influence on basin response times

Along with the accumulated rain, the intensity constitutes the other crucial indicator of episode magnitude. According to Camarasa-Belmonte and Soriano (2014), torrential rainfall and flood events are characterized more by “how it rains” than “how much it rains”, because high intensities can control rainfall-runoff conversion processes by reducing significantly the initial infiltration soil capacity and generating runoff, even in unsaturated soils.

As the environment becomes more arid, intensity is more important than accumulated rainfall to generate runoff. Tarolli *et al.* (2012) found no correlation at all between runoff coefficient and rain depth for extreme events, suggesting that rain intensity had a stronger influence than accumulated rain on runoff generation. Zoccatelli *et al.* (2019) verified this idea and highlighted the role of the aridity, by contrasting flood generation in desert and Mediterranean catchments.

Camarasa-Belmonte (2016) found a significant correlation between rain intensity indicators and the basin response times, especially lag time. As maximum intensity increased, lag time decreased (Fig. 4). Duration of lag time showed a clear seasonal behaviour, being shorter in summer and early autumn, when rainfall episodes were more intense.

However, besides the magnitude of rainfall intensity, the flood generation is conditioned by the moment, at the beginning or the end of the storm, by which time the maximum intensity is reached (Dunkerley, 2012). The influence of rainfall structure on the hydrograph shape can be observed in Figure 5, by comparing accumulation curves of rainfall and discharge in two events registered in Carraixet basin (September 1990 and December 2007) (Camarasa-Belmonte, 2016).

In the event of September 1990, maximum intensity (80 mm/h) occurred at the beginning. The catchment barely had time to react and hydrograph reproduced the shape of hyetograh (lag time 1.6 h). In December 2007 maximum intensity was lower (11.5 mm/h) and took place at the end of the storm. Rainfall-runoff processes were influenced by the operation of the basin and, in consequence, the accumulated curves of rain and flow differed greatly. Lag time was longer (11.5 h).

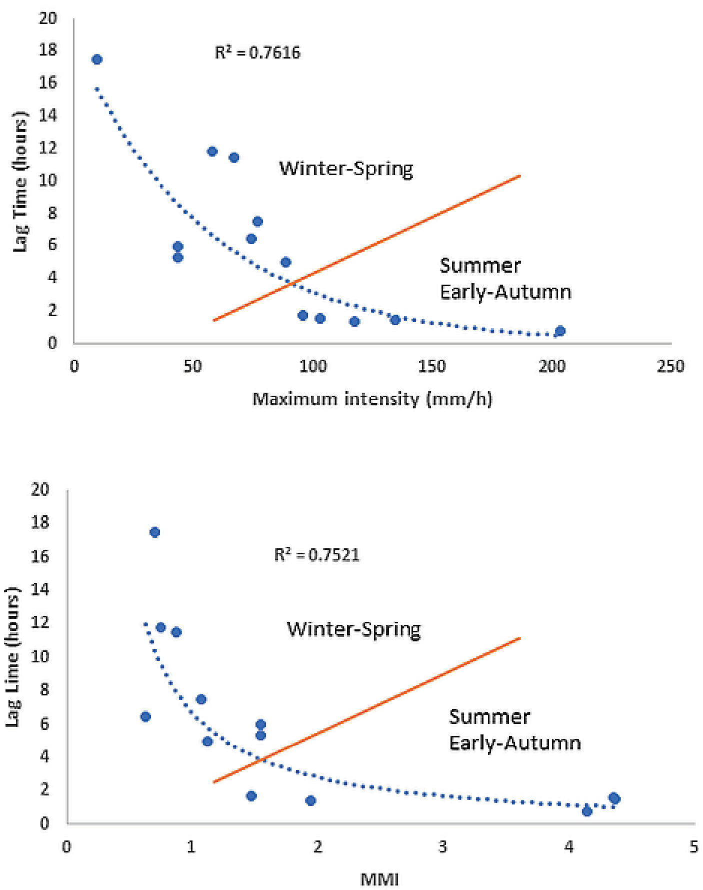
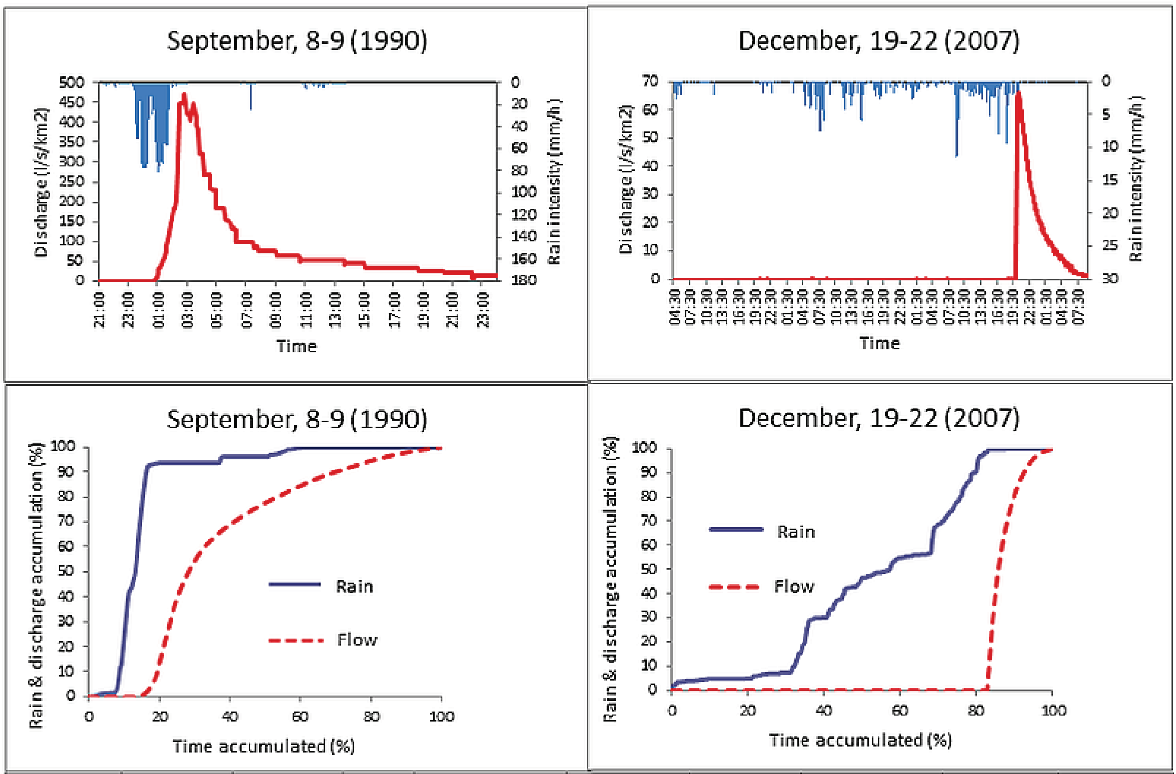


Figure 4. Influence of maximum intensity and MMI on lag time.



Event	Accumul. Rainfall (mm)	Max. Intensity (mm/h)	MMI	Runoff threshold (mm)	Runoff coefficient (%)	Runoff deficit (mm)	Peak flow (l/s/km^2)	Flood volume (mm)	Lag Time (hours)
Sep-1990	137	103	4,3	77	5,7	129	468	7,9	1,6
Dec-2007	42	67	0,8	30	2	41	66	0,8	11,5

Figure 5. Comparison between hydrographs and accumulation curves of rainfall and discharge (Carraixet, September 1990 and December 2007).

In order to analyse the influence of the intensity structure on the hydrograph, Camarasa-Belmonte (1016) developed the Momentum of Maximum Intensity Index (MMI). The MMI was applied to different flash floods registered at Carraixet basin under dry antecedent moisture condition (AMC I), and concluded that two types of event could be distinguished:

(i) Events where higher intensities occurred, concentrated at the beginning of the episode (high values of MMI). Hydrographs reproduced the shape of the hyetographs (showing very similar rain and discharge accumulation curves), because the catchment did not have time to intervene in rainfall-runoff conversion processes. Runoff thresholds were low and the response times of the catchment were very short (lag time of around 1h). In these cases, the hydrological connectivity was due to high intensity and peak flow which used to be high and fast (time to peak, around 1h). These types of episode generate the most dangerous flash-floods, from the point of view of risk, because a high flow peak can be quickly reached, leaving the population with no time to react.

(ii) Events where higher intensities occurred at the end of the episode (low values of MMI). In these cases, hyetographs and hydrographs did not show the same structure, because the catchment influenced the outputs (infiltration and other rainfall-runoff conversion processes modified the inputs's shape). Runoff thresholds were greater (as well as peak flow) and hydrological connectivity was due to accumulated precipitation. The response times of the basin were longer, so the population had more time to react and risk could be prevented. Even though the hydrograph showed a sharp peak, these types of episode could be interpreted as resource because they provided water to the fluvial system (filling either, surface and subsurface storages).

In summary, when maximum intensities occurred at the beginning of the episode, lag times were reduced and the structure of inputs (rain) and outputs (discharge) were very similar. Flash-flood was quickly generated and transferred along the channel network, creating a very risky situation for the population. However, when intensities occurred at the end of the episode, the model changed. The basin influence was higher, as well as water storage, that is runoff thresholds increased and runoff coefficients decreased. Lag time was longer and so was the time to react to risk. Thus, in this type of episodes resources increased and risk decreased. Camarasa-Belmonte (2016) also observed certain seasonality of events. The most dangerous flash-floods tended to be generated in summer and early autumn (caused by powerful convective cells), while those associated with the resource tended to be produced in spring and winter (associated with frontal rains).

Concerning the October 2018 event registered in Vernissa (Fig. 2), the first, second and final flow-peaks will be analysed. The first one (59 m^3/s) was caused by the highest intensity (33.4 mm/h) which occurred at the beginning of the storm. The catchment reacted quickly (lag time 5h 30'). The second peak was lower (36.7 m^3/s) due to reduced intensity (20.17 mm/h). Thus, even though there was base flow with a consequent decrease in the channel friction, the lag time increased (7 h). The final peak (17.49 m^3/s) was produced by low rainfall intensity (14.34 mm/h), but after several floods the channel travel time was reduced (lag time 5h 20').

4.2. Flash flood evolution under environmental change conditions

Once the specificity of ephemeral stream hydrology has been highlighted, an analysis of future trends of these systems under current environmental change condition proceeds. Climate change is destabilizing natural systems. However, the anthropic pressure, far from alleviating the situation, contributes to disturbing the morphogenetic balance of ephemeral streams. Obviously, this synergy implies a significant increase in flash-flood risk in systems which, due to the intermittence of flow, are not perceived as areas at risk, thereby increasing their vulnerability.

4.2.1. Climate change: rainfall event trends

Nowadays, it is unquestionable that the climate is changing. According to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, an increase in the average temperature of the planet is expected until 2100, between 0.3º and 1.7º for the best-case scenarios and, between 2.6 and 4.8º for the worst-case scenarios. The effects on precipitation and flow are not clear, because of the considerable variability of rainfall, especially in transition environments such as Mediterranean areas. However, there is consensus about the increase intense events in the world (Xoplaki *et al.,* 2012; Romera *et al.,* 2017). Under a general climate change, arid and semi-arid zones will suffer the worst impact due to its precarious water balance.

In Spain, even though general tendencies cannot be entirely confirmed, the studies point to a decrease in average precipitation during winter, spring and summer, and an increase in intensity in Alicante and Murcia (Valdés-Abellan *et al.,* 2017). According to most indicators the Mediterranean side will experience the greatest impact because of a marked decrease in Atlantic rains, which mainly affect inland areas, between the spring and summer transition (Miró *et al.,* 2015; Marcos-García and Pulido-Velazquez, 2017). González-Herrero and Bech (2017), in their study on rainfall episodes in Spain (1805-2014), found that the frequency of heavy rains increased (especially on the Mediterranean coast), while accumulated precipitation remained stable. Olcina (2017) also verified an increase in flood events due to heavy rains in Alicante between 1977 and 2016.

Camarasa-Belmonte *et al.* (2020) carried out a study on rainfall evolution between 1989 and 2016 in the territory of Jucar Water Authority where 698 episodes were selected and characterised according to their indicators of accumulated rainfall, intensity and persistence. Using an objective cluster analysis, episodes were classified into three types:

1. Episodes of high frequency and low magnitude; interpreted as limited resource free of risk.
2. Episodes of low frequency and high magnitude, that bring abundant water resources to the system, but which can also involve risk; described as high resource not risk free.
3. Episodes of intermediate frequency and heavy intensity clearly interpreted as high risk and low resource.

The analysis of event tendency showed an increase in intensity and a decrease in accumulated precipitation for the three types of episode (which means greater risk and less resource). Figure 6 shows this trend for episodes type 2 (high resource not risk free). Heavy rainfall involves associated risks concerning daily life disruptions (traffic congestion, overflow of urban pipes, etc.) provoked by intense rainfall *in situ*. In other words, Mediterranean events are becoming increasingly dangerous.

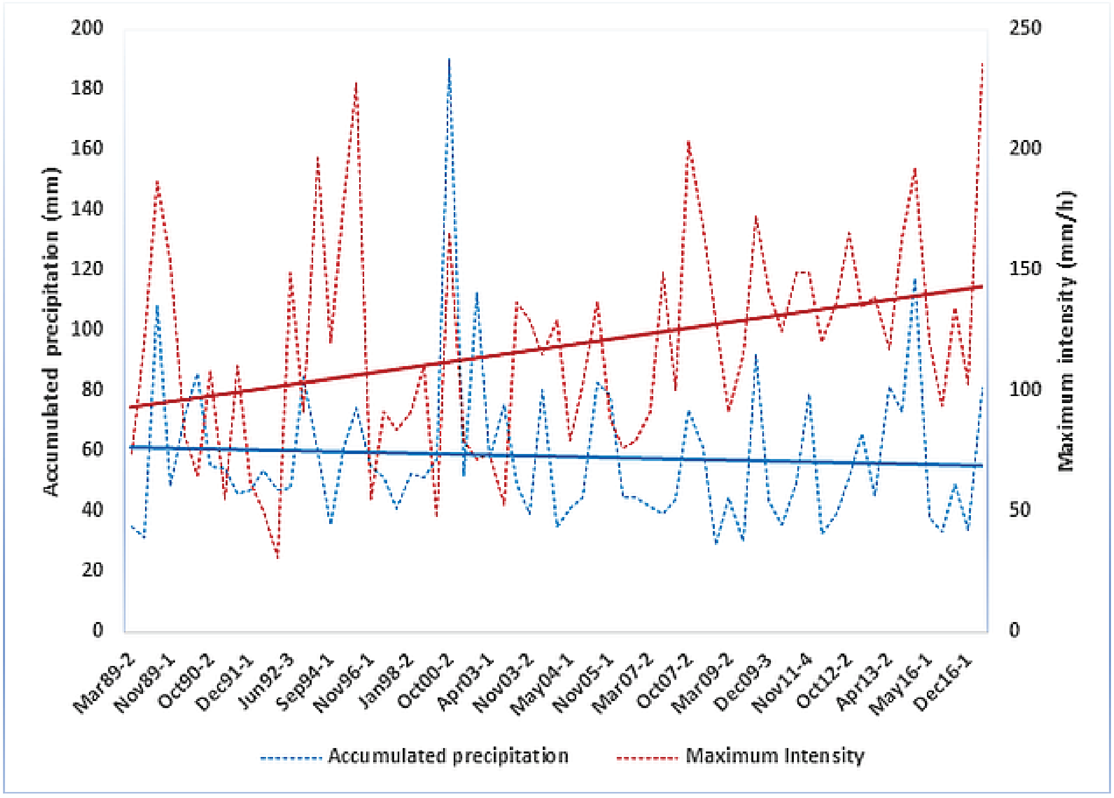


Figure 6. Trend of accumulated precipitation and maximum intensity in episodes type 2 (high resource not risk free), between 1989-2016, in the Jucar River Water Authority.

Consequences of climate change to Mediterranean ephemeral streams are very uncertain and controversial (Zoccatelli *et al.,* 2019). Yair and Kossovsky (2002) suggest "the possibility that the same regional climatic change might have different, or even opposite, effects on the hydrological regime". According to these authors, in semi-arid areas the shift to drier and warmer conditions could increase connectivity because the expected loss of vegetation would reduce infiltration and increase both runoff and soil erosion. Conversely, in arid areas connectivity would decrease, being limited to very extreme events. Yair and Raz-Yassif (2004) highlight the role of the scale. Thus, at headwaters runoff could increase due to the very low rain threshold required to produce flow in rocky areas (supposing erosion had removed soil and sediments). However, at a basin scale, water losses could increase because of channel transmission and other sedimentary forms, so connectivity would depend on antecedent moisture and rainfall intensity.

In summary, expected changes in ephemeral streams, derived from the increase in rainfall intensity and decrease of accumulated rainfall, apparently point to the idea of an increase of risk. At basin scale, connectivity will be determined by the intensity rather than by the accumulated rain, thereby making the flow response and the generation of flash-flood more impulsive. Consequently, lag time will be reduced, as well as the reaction time of the population to floods, which increases the risk. At the same time, water resources would be reduced due to fast drainage of surface flow. The "lack of time" for water to infiltrate will hinder water storage in natural reservoirs of basin (channel, piedmonts, sediments, flood-plain...).

4.2.2. Anthropic change: degrading natural systems and accelerating the water cycle

Despite the intermittency of surface resources, the Mediterranean environments have supported a strong agricultural use for more than 8,000 years. Historically, sustainable exploitation was achieved through soil conservation, water use and control of flood and erosion risks. According to Butzer (2005), the Mediterranean environment, often described as highly degraded, has been able to develop strong ecological and human resilience against degradation. However, recent changes in land use are dangerously compromising these precarious balance resources/risks (Barredo and Engelen, 2010; Durán *et al.,* 2014).

Changes mainly affect two basic aspects: (1) the rain-runoff conversion processes and (2) the way ephemeral-streams operate as drainage systems. The anthropic action causes alterations in the runoff generation (essentially through changes in land use) and in drainage through engineering interventions on river beds and areas of flooding.

4.2.2.1. Runoff generation and soil losses

Camarasa-Belmonte *et al.* (2018) analysed the effects of land use changes (1956-2011) on runoff generation and soil loss at Carraixet basin (Fig. 7). Only 26% of basin area maintained the same use, while 74% showed different changes, mainly a decrease in dry land (32%) due to the citrus increase (15%) and a lost in forest mass (23%) in favour of scrub and artificial cover (13%).

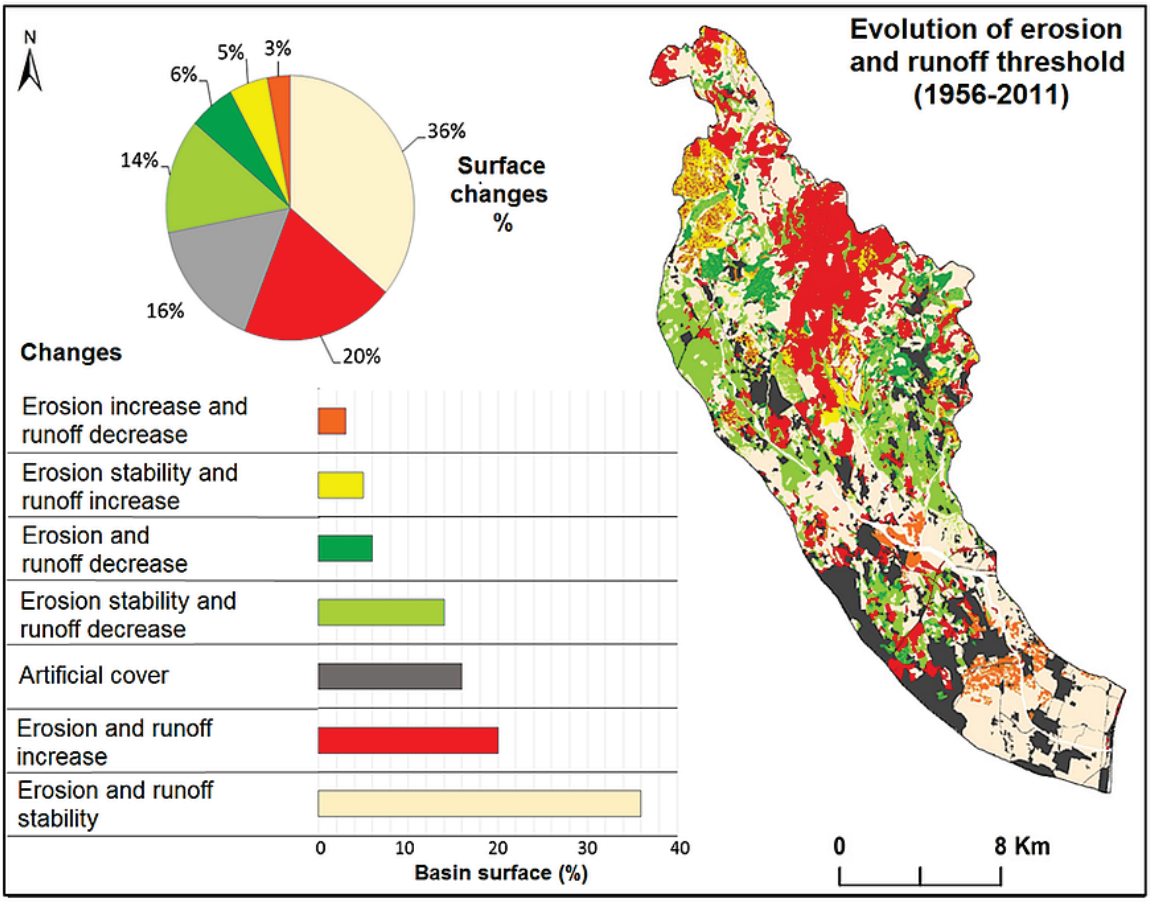


Figure 7. Combined evolution of erosion and runoff balances in Carraixet basin between 1956 and 2011 (Source, Camarasa et al.*, 2018, modified).*

The natural system reacted by adapting the erosive dynamics and runoff generation processes to new uses. According to this study, runoff production processes reacted faster and more intensively than soil loss. Thus, while erosive changes affected 33% of basin surface, changes in runoff production, which were much more dynamic, affected 62%. The whole area has been affected by both the runoff process and the soil loss process, with only 36% of the basin remaining stable. 64% of the area simultaneously presented alterations to both the erosion and runoff processes, showing negative synergies towards degradation (20%) and positive synergies towards improvement (6%).

In summary, anthropic land use modifications are significantly altering the resource-risk balance, increasing the erosion and flood risk, and decreasing water and soil resources.

4.2.2.2. Decreasing water basin storage and accelerating drainage

As mentioned before, the rainfall intensity increase can unbalance rainfall-runoff processes, generating runoff in soils which are not saturated. Therefore, discharge concentrates rapidly, generating flash floods which are very dangerous from the point of view of risk. The water cycle accelerates because infiltration is reduced. Artificializating and sealing the soil increases the process. The water that should be stored in soils, terraces and other sedimentary forms is drained into the sea, in a few hours, without having filled the different natural reservoirs of the basin. From the point of view of resources, this means significant losses for both natural ecosystems and human activity.

Given this scenario most structural flood control measures contribute to reducing the time permanence of water in the system. Anthropic interventions in which river beds are shortened and straightened, especially those that meander, are very frequent. Engineering works increase drainage speed by rectifying and widening the channels, decreasing friction and increasing their slopes. Along with the evacuation speed, the erosive power of the waters accelerates. As a consequence, the channel loses the hydrological connectivity with the adjacent geomorphological units (terraces, plains, etc.) and drains the excess water into the sea quickly as there is insufficient time and space to transfer water to the aquifers.

According to Camarasa-Belmonte (2020) "high energy events must have time and space to be regulated. Anthropogenic intervention should not contribute to draining resources from the basin as soon as possible, but rather to storing them naturally, because otherwise we are contributing to an increase in risk, a decrease in the resource and a destabilization of the system". In this sense, new green-blue adaptive initiatives are becoming increasingly common, compared to the usual grey flood control infrastructures (Alves *et al.,* 2019). The aim is to restore water balance in headwaters (runoff-producing areas) while maintaining maximum hydrological connectivity in the whole basin. In terms of river restoration, geomorphological strategies are being used which respect the so called "Territory of River Mobility" (channel, river corridor and part of the floodplain used by the river for energy readjustments) (Ollero, 2015). Thus, floods are laminated, the peak flow is reduced, part of the water is transferred to the aquifers, and the amount of resource which is discarded into the sea is delayed and reduced.

4.2.3. Geomorphic change: morphogenetic disequilibrium process-form

The geomorphological evolution of semi-arid fluvial systems occurs because of the morphogenetic action of extreme events (Brakenridge, 1988). According to Graff (1988) in Mediterranean environments, processes control forms in episodes of great magnitude, while forms control processes in those of low magnitude. Therefore, the magnitude of episodes is crucial for landscape changes. In this sense, according to Bull (1997), ephemeral streams are morphogenetic systems which are continuously imbalanced, since during high energy events, channels and floodplains adapt to large peak flows, while for the rest of the time, the channels begin to be filled with sediments and vegetation in order to adapt the forms to low discharge or even an absence of flow.

Wolman and Gerson (1977) introduce the concepts of *effectiveness* and *recovery period* to assess the geomorphic work done by individual events in a particular morpho-climatic environment. Thus, the effectiveness is "the ability of an event or combination of events to affect the shape or form of the landscape", while recovery period is "the time required for a landform to recover the form existing prior to the event". According to these authors, large low-frequency events make up the landscape whereas restorative processes act during episodes of high frequency and low energy, to recover original morphology. This equilibrium is closely linked to morphoclimatic environments. Thus, after extraordinary events, channels of humid environments could take between a few months and a few years to recover their shape those of semi-arid environments could require several decades, and those of arid environments could take hundreds of years, or in fact might never recover their initial form (Wolman and Gerson, 1978).

At this point the question is how environmental changes would affect the morphogenetic activity in ephemeral streams. Figure 8 illustrates trends for episodes registered at the Jucar Water Authority from 1989 to 2016. Figure 8a shows an increase in high intense episodes, while Figure 8b reveals how the efficiency of frequent low magnitude events is decreasing. Due to climate change, morphogenetic phases could intensify in the long term because of the intense episode augmentation with high erosive efficiency. At the same time, the system restoration capacity would be reduced because the efficiency of low magnitude episodes is decreasing, thereby increasing recovery times. These trends contribute to the destabilization of Mediterranean fluvial systems and again point to the increase in risk and the reduction of resources.

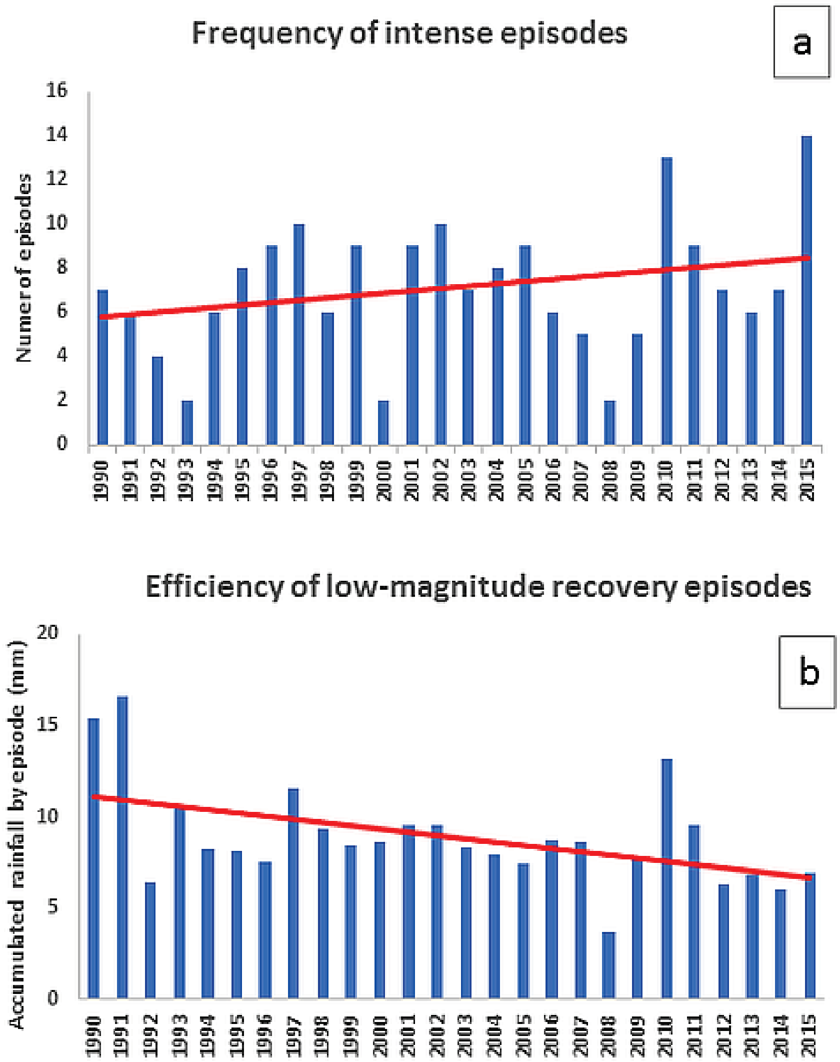


Figure 8. Evolution of episodes in the Jucar River Water Authority (1989-2016). a) Frequency of intense episodes; b) Efficiency of low magnitude recovery episodes (Source: Camarasa-Belmonte, 2020 modified).

5. Conclusions

Mediterranean ephemeral streams are intermittent flow river systems which involve a greater risk of flooding than initially expected. Environmental planning and land use legislation are increasingly aware of their hydro-geomorphological specificities. That is how the European Flood Directive supports the analysis of this type of basin, on a detailed scale and adapting the methodology to its characteristics. The present work, based on the compilation of previous studies carried out in eastern Spain, highlights the key issues that define Mediterranean hydrology and its foreseeable evolution in a context of environmental change.

Two basic characteristics are crucial for flood generation in ephemeral streams: the intermittency of flow and the magnitude of episodes (which makes flow continuity towards the mouth possible). Due to the catchment hydro-geomorphological configuration, channels are disconnected from the aquifers, and flow depends exclusively on the rain. However, not all episodes generate runoff. Only major events ensure sufficient connectivity between the different elements of the basin (especially sedimentary transitional forms) in order to generate flow.

The magnitude of episodes can be described by the volume of accumulated water as well as by the intensity of rainfall. The accumulated precipitation mainly determines the volume of the hydrograph and the peak flow through its influence on the water balances (significant correlation between accumulated rainfall and the deficits and runoff thresholds have been found). Maximum intensities determine the response times of basins, evidenced by the significant negative correlation between maximum intensity and catchment lag time. Furthermore, not only are maximum intensity values important, but also the moment at which they occur, namely either at the beginning or at the end of the storm. When the highest intensities occur at the beginning of the storm, catchment lag time is reduced and a great similarity between rain and discharge can be observed. The basin hardly has time to intervene in rainfall-runoff conversion processes, thus runoff thresholds drop and runoff coefficients rise. Conversely, when maximum intensities occur at the end, the basin influence is evident, water transfers to the aquifer augment, runoff coefficient and peak flow decrease, and lag time increases. Consequently, events with high intensities at the onset of rainstorm entail a significant risk, whereas if the maximum intensities are lower and recorded at the end, they constitute a resource.

The trend in Mediterranean episodes is towards increasing intensity and decreasing accumulated rainfall. As a consequence, hydrological connectivity will become more dependent on rain intensity, thus reducing runoff thresholds (less water storage) and basin response times. Anthropic changes enhance this behaviour, by reducing infiltration and increasing surface runoff and erosion while accelerating the hydrological cycle.

Focusing on the current context of environmental change, the evolution of ephemeral streams hydrology points to a clear increase in risk to the detriment of the resource. This behaviour, which is more pronounced inland than on the coast, makes it difficult to store resources in headwaters (which are mostly located inland), and at the same time it increases risk downstream in more populated floodplains on the coast. Conversely, from an anthropic point of view, changes in land use and flood control structural measures, far from alleviating the problem, accelerate the drainage of water into the sea, making it difficult to store the resource in the basin's natural reservoirs (soils, terraces, aquifers). As a consequence, in the long term an increase of process-form disequilibrium in Mediterranean ephemeral streams can be expected, as well as a progressive aridification of these fluvial systems.

Reversing this trend implies adaptation strategies based on flexibility. We must be aware that a large part of flood control, mitigation and management measures of the 20th century have become obsolete today because they are too narrow and rigid. We cannot forget that we are in a context of change, and natural systems need time and space to adapt. In this sense, conservationist approaches to the environment should prevail because reducing risk involves developing resilient systems compatible with natural dynamics. Therefore, increasing knowledge of ephemeral stream hydro-geomorphology is essential to developing 21st century solutions to the problems of the current and following centuries.

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SYNOPTIC CAUSES OF TORRENTIAL RAINFALL IN SOUTH-EASTERN SPAIN (1941–2017)

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ABSTRACT. The weather types of 68 dates with torrential rainfall (≥200 mm/day) recorded at any weather station in the provinces of Alicante or Murcia during the period between 1941 and 2017 were determined using the Martín-Vide's 1984 manual synoptic classification. Other relevant synoptic characteristics, as well as the surface pressure, and the value of the Western Mediterranean Oscillation index (WeMOi) on which those dates fell were also considered. The results show the high percentage of the Advection from the East with DANA (isolated high-altitude depression) or 'gota fría' type, which is present in more than 50% of the events, followed by the Trough type at 500 hPa and the Dynamic or Cold-core Low type, in the torrential rainfalls of South-eastern Spain. Except for the latter type, the average air pressure is close to or higher than normal. The WeMOi was negative for all events, which is consistent with the nature of this teleconnection pattern.

Causas sinópticas de las precipitaciones torrenciales en la región del Sureste, España (1941-2017)

RESUMEN. Se han determinado los tipos sinópticos, a partir de la clasificación manual de Martín-Vide (1984), de 68 fechas con precipitación torrencial (≥200 mm/día) en alguna estación meteorológica de las provincias de Alicante y Murcia durante el período 1941-2017. Se han considerado otras características sinópticas relevantes, así como la presión en superficie, y el valor del índice de la Oscilación del Mediterráneo Occidental (WeMOi) de las citadas fechas. Los resultados muestran la importancia porcentual en las precipitaciones torrenciales del Sureste de España de las advecciones del este con DANA ("gota fría"), presentes en más del 50% de los casos, seguida por las vaguadas en 500 hPa y las borrascas dinámicas o frías. Salvo en este último tipo, la presión atmosférica media es próxima o superior a la normal. En todos los casos el WeMOi fue negativo, lo que es consistente con la naturaleza de este patrón de teleconexión.

Key words: DANA, South-eastern region (Spain), synoptic situation, torrential rainfall.

Palabras clave: DANA, región del Sureste (Spain), situación sinóptica, precipitación torrencial.

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1. Introduction

Rainfall in the South-eastern region of Spain is known to be extremely irregular both spatially and temporally. In particular, its high daily concentration of rainfall (Ayala Carcedo and Olcina, 2002; Martín-Vide, 2004; Cortesi *et al.,* 2012; Monjo and Martín-Vide, 2016; Serrano-Notivoli *et al*., 2018) and degree of variability from one year to the next, indicated by a coefficient of variation of up to 40% among annual pluviometric series (Martín-Vide, 2011), combined with the marked aridity of the region which is due to its sparse precipitation, mild temperatures and abundant insolation, give rise to a semi-arid Mediterranean climate which sometimes recalls the edges of the desert (Conesa and Alonso, 2006; Martín-Vide and Olcina, 2001). The exceptional nature of the rainfall in South-eastern Spain gives the landscape a distinctly barren, rugged and dusty appearance which contrasts sharply with the verdant vegetation of its irrigated spaces. On the other hand, the region is rich in biodiversity and endemic species and is known for the adaptation of its culture and technology to the scarcity of water and irregularity of precipitation over the course of centuries (Belmonte *et al*., 2017).

An analysis of the daily precipitation values at the region's observatories immediately reveals that the record is punctuated with days of very high rainfall compared to the modest annual average, with the recorded rainfall on some days accounting for more than 50% of the annual total. The occurrence or absence of such days can radically alter the character of a year from rainy to dry, or vice versa. Moreover, it is not uncommon for a markedly dry year to later be classified as rainy due to the occurrence of a day or two of torrential rainfall during the autumn. In summary, we find ourselves in a region with one of the highest degrees of pluviometric irregularity (Monjo and Martín-Vide, 2016) on the planet; this is a challenge for the statistical analysis of precipitation volumes, particularly in terms of daily and sub-daily rainfall.

This paper focuses on the synoptic causes of torrential rainfall in South-eastern Spain. In this regard, previous studies have presented the synoptic features of the torrential rainfalls in the region and their hydrological effects, primarily the resultant floods (Gallego Jiménez, 1997; Gil Olcina *et al*., 2004; Gilabert and Llasat, 2018). These studies emphasise the significance of cold air pockets at high altitudes, the 'gotas frías' or isolated high-altitude depressions (cut-off lows), the troughs in altitude, etc., that is to say, the importance of circulation in the middle and upper tropospheric levels, to the genesis of the South-eastern floods. Some studies compare them to the temperature of the surface waters of the Mediterranean (Millán *et al*., 1995, 2005; Pastor, 2012; Pastor *et al*., 2001, 2015). Others present spatial patterns (Peñarrocha *et al*., 2002). There are also studies that analyse one or several catastrophic events resulting in significant material losses in terms of agriculture, infrastructure and cities (Capel Molina, 1974; Pérez Cueva and Armengot, 1983, Gil Olcina, 1986; Pastor *et al*., 2001, Olcina *et al*., 2010; Espín *et al*, 2017., etc). Still others reconstruct historical episodes (Barriendos *et al*., 2019). The relationship between intense rainfall and soil erosion in a region with a high intensity of erosive and desertification processes is a subject of particular focus (Romero Díaz *et al*., 1992, 1998; Peña-Angulo *et al*., 2019). Some indicate the possible trends under climate change (Millán, 2014).

Despite the extensive literature on the phenomenon of torrential rainfall and the resulting flooding and washouts in the study area, there has been no systematic study of its atmospheric genesis over a long and recent period for the provinces of Alicante and Murcia combined; this is the *leitmotif* of this paper, which is structured as follows: Section 2 presents the baseline data and study area, Section 3, the methodology, Section 4, the results, Section 5, a discussion of the results, and Section 6, the conclusions.

2. Data and study area

There are three types of baseline data: pluviometric, synoptic and teleconnective.

a) The pluviometric data are comprised of the dates on which the precipitation recorded at any meteorological station in the Júcar and Segura catchment areas in the provinces of Alicante and Murcia during the period from 1941 to 2017 was equal to or greater than 200 mm/day.

b) The synoptic data comprise the reanalysis at the surface and at 500 hPa from NOAA (and CFSR as of 2014) at noon on those dates.

c) The teleconnective data are the daily values of the Western Mediterranean Oscillation index (WeMOi) (Martín-Vide and López-Bustins, 2006) for the aforementioned dates.

The pluviometric data come from stations operated by the AEMET (Spanish Meteorological Agency), formerly INM (National Institute of Meteorology) and SMN (National Meteorological Service), and from the Júcar (CHJ) and Segura (CHS) catchment areas. We identified a total of 68 dates with at least one recorded rainfall of 200 mm or more; this constitutes a statistically significant sample for determining the synoptic situations that generate this type of precipitation. These were the observational data used by Miró *et al*. (2017) for the reconstruction of daily volumes of torrential rainfall events. Due to the changing number of weather stations over the course of the study period, the homogeneity of the series cannot be guaranteed; however, homogeneity is not required, as trend analysis is not the subject of this paper. Even without the inclusion of all the occurrences, the 68 dates constitute a sufficiently broad set for determining the synoptic situations which trigger torrential rainfalls in the region, as well as their characteristics.

As expected, there are some consecutive dates among the 68 events where the torrential episode lasted more than one day, although we cannot rule out the well-known effect of the incorrect assignment of a record to a given date in some cases.

The synoptic information was obtained from the German portal *Wetterzentrale* (www.wetterzentrale.de) which contains several reanalysis files. We used the NOAA (USA) file that covers the entire study period except for the last four years, from 2014 to 2017, which are covered by the reanalysis from the same institution CFSR (*Climate Forecast System Reanalysis*) and which is available on the same portal. The combined surface and 500 hPa maps have proven optimal for applying a manual classification of synoptic situations to the 68 dates analysed.

The study area was limited to the provinces of Alicante and Murcia although geographically, the South-eastern region covers the whole of Almeria and a part of Granada that borders with the latter, as well as a section of Albacete that borders on Murcia (Fig. 1). Strictly speaking, the relatively wet northern tip of Alicante, with its average annual volumes exceeding 600 mm, and occasionally 800 mm, could be excluded. The provinces of Alicante and Murcia were selected due to the availability of precipitation data (Miró *et al*., 2017). At any rate, most of the selected events could have affected the provinces bordering the two comprising the study area. There are many more dates in Alicante than in Murcia, partly due to the weight of northern Alicante which, combined with southern Valencia, exhibits the maximum daily rainfall and the highest hourly and sub-hourly intensities in Spain (Pérez Cueva, 1994). Downpours of more than 100 mm but less than 200 mm in a day are relatively abundant at Murcian weather stations but are not among the selected events, as the threshold was established at 200 mm; in contrast, daily records exceeding 200 mm are relatively frequent in northern Alicante under the same synoptic situation, with an average of about two cases per year (Riesco and Alcover, 2003).

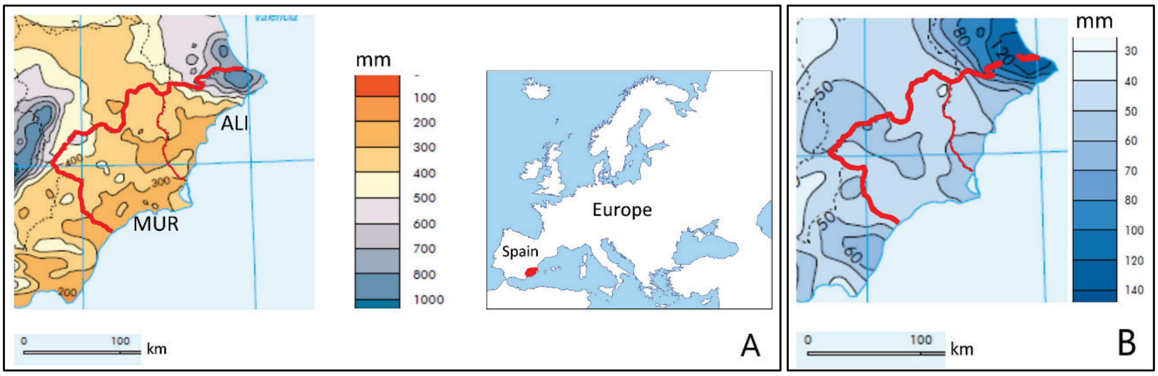

Figure 1. a) Study area (Alicante and Murcia provinces) with the annual rainfall average, and its localization in Europe; b) Annual maximum precipitation average. Source: Obra derivada de MapANE 2015-2017 CC-BY 4.0 ign.es.

3. Methodology

The methodological steps were as follows:

1) Identification of dates in the observational database with a precipitation of 200 mm or more recorded in at least one weather station in the provinces of Alicante and Murcia during the period from 1941 to 2017. There were 68 dates in total, which constitute a large statistical sample. Monthly and seasonal distributions of the identified dates were obtained.

2) Determination of the weather type of the dates identified using the manual synoptic classification of Martín-Vide (1984), from the noon reanalysis of NOAA (and CFSR from 2014 to 2017) found on the Wetterzentrale portal mentioned above. Only two events were classified as types that differ slightly from the 16 in Martín-Vide's classification (1984). In addition, the term DANA has been used in this classification instead of 'gota fria'.

3) Annotation of other relevant synoptic characteristics of the classified dates on a continental scale, as well as the atmospheric pressure in the study area.

4) Calculation of the frequency of the weather types of the classified dates, as well as the average air pressure and WeMOi of each type.

5) Selection of a surface weather and 500 hPa topography map as a model of each of the most frequent weather types.

4. Results

The first five columns of Annex present the selected dates with the meteorological stations which recorded 200 mm of precipitation or more during the study period; this information was obtained from the Miró *et al*. (2017) database. This is followed by the weather type determined using Martín Vide's 1984 synoptic classification, the surface atmospheric pressure, synoptic characteristics on a continental scale and the WeMOi value. Note that there may be several weather stations with records of 200 mm or more on the same date, but they will only be included in the analysis as a single event, with the '&' symbol in the columns for weather type, atmospheric pressure, synoptic characteristics and WeMOi for the same date, so as to avoid repetition.

The principal results for the 68 dates with torrential rainfalls are summarised in Table 1. The most relevant result is the high frequency of the Advection from the East with DANA type which was present in more than half of the events (52.9%), (Fig. 2). Lagging far behind the aforementioned weather type, but at frequencies which are not insignificant, are the Trough type (17.6%) (Fig. 3) and the Dynamic or Cold-core Cyclone (16.2%) type (Fig. 4). These three weather types combined account for 86.8% of the total (59 dates out of 68).

Table 1: Absolute and percentage frequencies of the synoptic situations on the dates with a precipitation of 200 mm/day or more at any observatory in Alicante or Murcia provinces, and averages of the atmospheric pressure and the corresponding WeMOi value (1941–2017). Source: Own elaboration.

Synoptic situation or weather type	Abs.Freq.	%	Mean Atm.Press. (hPa)	Mean WeMOi
Advection from the E with DANA	36	52.9	1016.4	-1.67
Trough	12	17.6	1015.1	-0.96
Dynamic or Cold-core Low	11	16.2	1008.7	-1.75
Advection from the E	5	7.4	1019.6	-1.48
Weak surface pressure gradient	2	2.9	1019.0	-1.18
Advection from the NE with DANA	1	1.5	1014.0	-0.66
DANA to the W	1	1.5	1014.0	-0.57

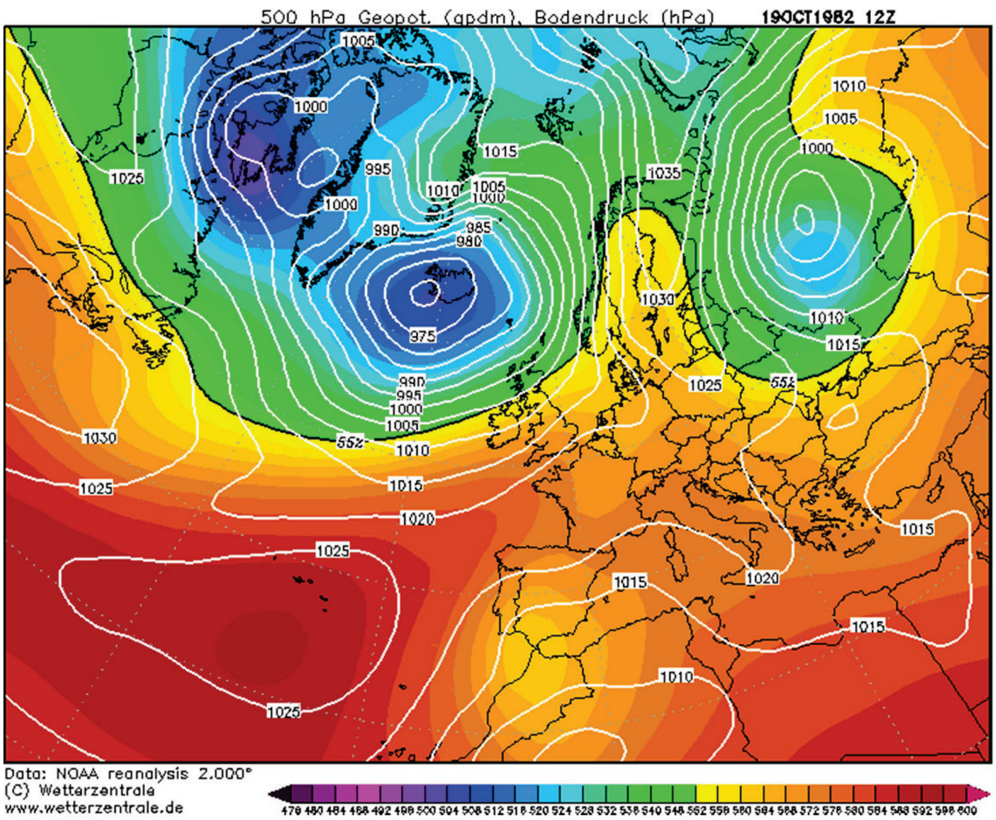

Figure 2. Advection from the East with DANA on 19 October 1982, at 12:00 UTC. Source: www.wetterzentrale.de.

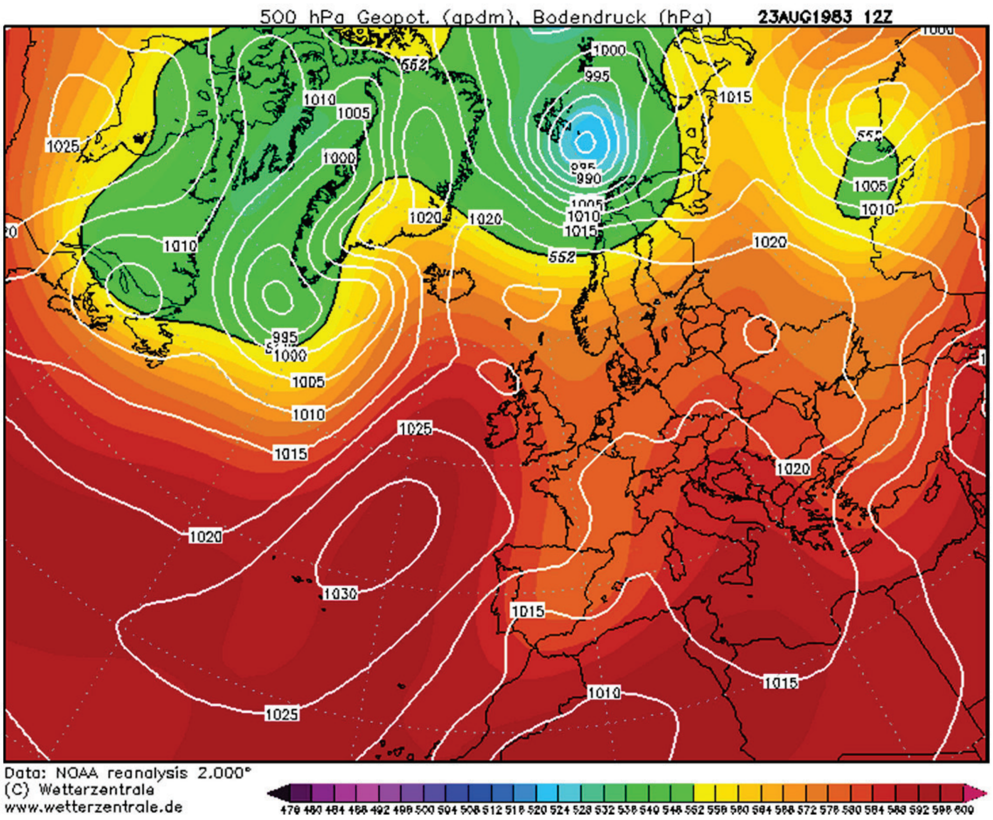

Figure 3. Trough on 23 August 1983, at 12:00 UTC. Source: www.wetterzentrale.de.

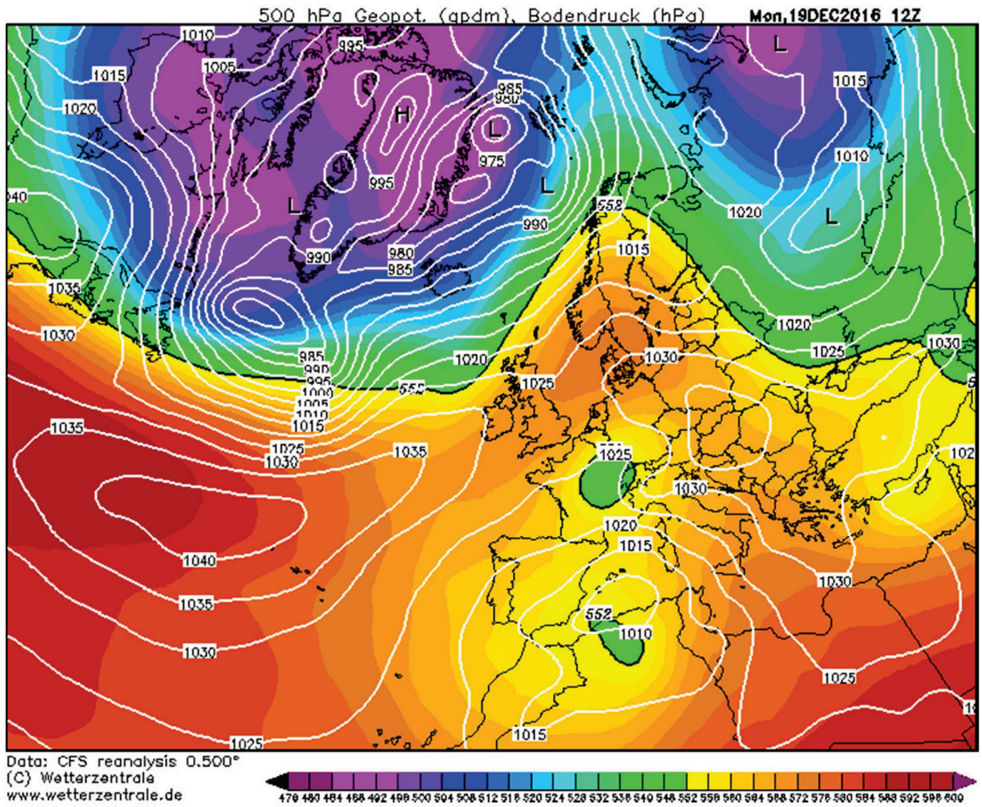

Figure 4. Dynamic or Cold-core Low on 19 December 2016, at 12:00 UTC. Source: www.wetterzentrale.de.

Flows with an eastern component (E and NE) on the surface occur in more than 60% of the events (61.8%)

The average atmospheric pressure for the 68 dates is 1015.2 hPa, higher than the normal at sea level (1013.2 hPa). The lowest average atmospheric pressure corresponds to the Dynamic or Cold-core Cyclone type (1008.7 hPa), and the highest corresponds to the Advection from the East without an upper-level Low type (1019.6 hPa), which ranks fourth in terms of frequency. The highest value was 1028 hPa on 14 November 1953, and the lowest was 1002 hPa on 7 May 2002.

For events with Advection from the East with DANA, the high frequency of anticyclones in central and northern Europe (83.3%), often with anticyclonic bridges between several nuclei or to the Azores High, is notable at a continental scale.

The WeMOi was negative on all the dates of the 68 events in the study; in 21 events, it was equal to or less than -2.0, an extremely negative value (López-Bustins, 2007). The average value is -1.5. The lowest was -3.03 on 10 October 2008.

The seasonal and monthly distribution of the dates demonstrates the well-known fact that autumn is the critical season, which accounted for nearly 70% of the events (69.1%), with the highest frequency in October (32.4%), followed by September (22.1%) and November (14.7%), while only two events were recorded in summer.

5. Discussion

The impact that the atmospheric mechanisms of the middle and upper levels of the troposphere, i.e. the troughs and the isolated high-altitude depressions or 'gotas frías' currently referred to by the acronym DANA, have in the genesis of intense or torrential rainfalls in Mediterranean Spain is well-known; however, the frequency revealed by the study is very striking. Specifically, the 'Advection from the East with DANA' weather type was present in more than half of the events in the study area (Martín-Vide, 1984).

The acronym DANA refers to an isolated high-altitude depression and has come to replace, with some nuance, the popular expression 'gota fría', or cut-off low (Palmén, 1949). A DANA results from the strangulation of a polar jet stream trough at latitudes similar to those of southern Europe, which gives rise to a cyclonic vortex in the middle and upper troposphere with the corresponding injection of cold air (Palmén, 1949; Martín-Vide, 1984; Quereda, 1989; Martín-Vide, 1989; Llasat, 1991; Gil Olcina and Olcina, 1999; Martín León, 2003; Nieto *et al*., 2005; Llasat et al., 2007; Munoz *et al*., 2019; Alshouhani, 2020).

After analysing six events that occurred between 2000 and 2012 in the Region of Murcia, Castejón Porcel and Romero Díaz (2014) also concluded that the existence of an isolated high-altitude depression is the critical situation for the occurrence of torrential rainfall. Due to their marine origin, the surface flows from the east provide the humidity necessary for large daily rainfall records, as well as the cold high-altitude depression, the necessary vertical thermal contrast and the unstable stratification which enables the triggering effect. The threshold of 200 mm which, even when distributed over many hours in a day, requires a high intensity of precipitation, probably increases the predominance of the DANAs with surface flows from the east in the genesis of the torrential rainfall in South-eastern Spain, which would perhaps not be so noteworthy at lower rainfall thresholds. In the Catalan provinces having a coastline and a lower threshold of 100 mm/day, several types other than the three most frequent types in the South-east were identified (Martín-Vide *et al*., 2008).

This does not contradict the known fact that not every isolated high-altitude depression produces copious or intense downpours (Llasat, 1991), as no contingency analysis has been carried out. However, when these downpours do occur, the existence of one of the three most frequent synoptic situations, Advection from the East with DANA, Trough, or Dynamic or Cold-Core Low, often linked in time, can be expected with a high degree of probability (86.8%) especially the first type. The synoptic causes of torrential rainfall on the Mediterranean side of the Iberian Peninsula differ significantly from those which produce light rainfall (Romero *et al*., 1999).

The specific location of the DANA is a decisive factor in the location of the precipitation peaks, which occur on the 'leading edge' of the depression, usually in the eastern or north-eastern sector of its periphery (Medina, 1976; Gallego Jiménez, 1997). The great diversity of the DANA locations also produces a varied spatial distribution of maximum rainfall in the region. The demanding threshold of 200 mm/day favours northern Alicante, where the orographic conditions and the orientation of the coastline promote very high records (Pérez Cueva, 1994).

The Advection from the East with DANA type forms a characteristic pattern on a continental scale with high pressures in central and northern Europe, often with an anticyclonic bridge to the Azores High. The anticyclone over the continent is characteristic of a blocking anticyclone, i.e. it is persistent (Barriopedro *et al*., 2006). The occurrence of blocking anticyclones over the British Isles, where rain is absent for one or two weeks, is particularly well known, while intense showers and downpours occur in southern Europe, particularly in the south and east of the Iberian Peninsula.

The next most frequent weather type after Advection from the East with DANA is the Trough which occurs at 500 hPa, often during the torrential rainfall events of the South-east is the former type prior to the detachment from the jet stream that characterises the isolated high-altitude depression, or DANA. The variety in the arrangements of trough axes, from parallel to highly oblique with respect to the meridians, and their situation to the west, above or to the east of the study area, explains the location of the highest records which generally coincide with the ascending or eastern branch of the trough (Medina, 1976; Martín-Vide, 1984; Gallego Jiménez, 1997).

The third weather type, Dynamic or Cold-Core Low, is often the result of the surface reflection of a DANA after a certain amount of time (Martín León, 2003). There are no noticeably low surface pressure values in the study area. The minimum record, 1002 hPa, is far above the usual surface pressure of the frontal or mid-latitude depressions of the polar front.

To elaborate on the topic of atmospheric pressure, it is usually higher than normal during torrential rainfall events in the South-east, except when a cold-core low is centred over the region. In contrast to what generally happens in the climates of Atlantic Europe, for example, the lack of a negative correlation between atmospheric pressure and precipitation in the east of the Iberian Peninsula is well known (Martín-Vide et al., 1999); this underscores the significance of the high-altitude mechanisms. Other studies of the Valencian Community, such as Armengot (2002), also found higher than normal pressures, including some which were substantially high, during the torrential events.

As for the effect that the WeMO pattern has on torrential rainfall in the South-eastern region, which was defined specifically to explain the variability that the NAO did not achieve for the eastern Iberian Peninsula (Martín-Vide, 2002; Martín-Vide and López-Bustins, 2006; López-Bustins, 2007), the results obtained are fully consistent with the nature of the aforementioned Mediterranean pattern. Its negative phase, or more precisely, the negative values of the WeMOi, corresponds to flows with an eastern component, which are humid in the eastern Iberian fringe, when a depression towards the south-west of the peninsula meets with high pressures in Central Europe and northern Italy. In view of the result demonstrating that the 68 events correspond to negative WeMOi dates, and in the 31% of the cases to extremely negative ones, we can conclude that the risk of torrential rainfall (≥200 mm/day) in the study area is practically zero, if the WeMOi is positive. The mean value of -1.5 of the WeMOi for all the study cases is consistent with the fact that the range of WeMOi values that recorded the maximum frequency of torrential episodes in Martín-Vide and López-Bustins (2006) was that of (-2, -1].

The surface flows of the eastern component, which are always humid, were present in more than 60% of the events, which is in line with the high water vapour contingent required for torrential episodes. In any case, there is still a significant 40% of events in which the contribution of humidity from

Mediterranean waters is not evident at a synoptic level; this indicates that mesoscale marine flows (Gómez *et al*., 2011) and the high local hygrometric content must be considered as possible contributions to these events.

The seasonal and monthly distribution of the dates demonstrates that autumn, during which approximately 70% of the events occurred, is the critical season with October as the most prominent month; this is known from the historical compilation and reconstruction of floods as well (Gil Guirado *et al*., 2019; Barriendos *et al*., 2019). The autumnal concentration of the events analysed corresponds to the most negative values of the daily WeMOi at the aforementioned station throughout the year; this was already recognised by Meseguer-Ruiz *et al*. (2018).

6. Conclusions

Advection from the East at the Surface with a DANA, or isolated high-altitude depression, is by far the most predominant weather type on days of torrential rainfall, assuming a threshold of ≥200 mm/day, in South-eastern Spain. It was present on more than 50% of the dates with precipitation records exceeding this threshold at any observatory in Alicante or Murcia. This weather type, in combination with the High-Altitude Trough type, sometimes prior to the formation of a DANA, and the Dynamic or Cold-core Low type, which sometimes follow a DANA temporally, when they are reflected at the surface, account for nearly 90% of the events. It is therefore quantifiably clear that the conditions of instability in the middle troposphere are decisive for the genesis of torrential rainfall in the South-eastern region. On the other hand, the surface flows of the eastern component, which are always humid, are present in more than 60% of events, which is in line with the high water vapour contingent required for torrential episodes.

On a continental scale, the Advection from the East with DANA type usually coincides with a blocking anticyclone in central and northern Europe, often forming an anticyclonic bridge to the Azores High. This is a typical pattern of the negative phase of the WeMO. On the 68 dates analysed, the WeMOi was negative, which is consistent with its pluviometric effects on the East Iberian and with the predominantly autumnal occurrence of the torrential rainfall events.

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Annex

Study events - Dates on which precipitation of 200 mm/day or more occurred at any observatory in Alicante or Murcia, synoptic situation, atmospheric pressure (hPa), other synoptic characteristics and WeMOi value (1941–2017). Source: Miró et al. *(2017) (columns 1 to 5) and author's research (columns 6 to 9).*

Meteorol. station	Lat.	Lon.	Date	mm	Synop. Situat.	hPa	Other synoptic characteristics	WeMOi
S. MIGUEL DE LAS SALINAS, CHS	38	-0.8	05/10/1941	264.6	Trough	1018	Very weak trough, Scandinavian A	-0.9
PUERTO LUMBRERAS, CHS	37.6	-1.8	21/10/1948	240	Advection from the E with DANA	1020	Azores A extended towards Cantabrian Sea	-1.51
PEGO CONVENTO	38.8	-0.1	14/11/1953	260	Advection from the E with DANA	1028	Very weak DANA, Central Europe A	-0.72
PEGO CONVENTO	38.8	-0.1	23/11/1955	233	Advection from the E	1023	Rhombus pattern in Atlantic Ocean	-0.92
CALLOSA D'EN SARRIA TOSSAL DE SALOMA	38.7	-0.1	10/10/1956	206	Weak surface pressure gradient	1017	NASH (North Atlantic Subtropical High)	-2.05
DENIA	38.8	0.12	01/10/1957	318,8	Advection from the E with DANA	1009	British Isles A	-1
DENIA	38.8	0.12	02/10/1957	343,2	Advection from the E with DANA	1009	A to the W of British Isles	-1.27
XABIA	38.8	0.17	02/10/1957	878	&	&	&	&
CAP DE SANT ANTONI	38.8	0.2	03/10/1957	409,7	Advection from the E with DANA	1014	A to the W of British Isles	-0.6
EL VERGER RACONS	38.9	0.03	15/10/1957	298	Advection from the E	1013	Anticyclonic bridge Azores-Europe	-1.18
XABIA	38.8	0.17	15/10/1957	300	&	&	&	&
DENIA	38.8	0.12	16/10/1957	239,4	Weak surface pressure gradient	1021	Azores A	-0.3
COCENTAINA, CONVENT	38.8	-0.4	26/10/1958	205	Advection from the E with DANA	1019	A over the Netherlands	-1.01
PANTANO DE BENIARRES	38.8	-0.4	27/10/1958	200	Advection from the E with DANA	1013	North Sea-Central Europe A	-1.71
XALO	38.7	0	07/06/1960	240,7	Advection from the E	1020	Azores A	-0.14
DENIA	38.8	0.12	30/10/1961	250	DANA to the W	1014	No baric gradient	-0.57
EL VERGER RACONS	38.9	0.03	30/10/1961	200	&	&	&	&

Meteorol. station	Lat.	Lon.	Date	mm	Synop. Situat.	hPa	Other synoptic characteristics	WeMOi
XABIA	38.8	0.17	30/10/1961	225	&	&	&	&
CAP DE SANT ANTONI	38.8	0.2	31/10/1961	224	Advection from the E with DANA	1018	------------	-0.79
PEGO CONVENTO	38.8	-0.1	02/11/1961	220	Advection from the E with DANA	1020	Azores A with bridge with Central Europe A	-1.35
PEGO CONVENTO	38.8	-0.1	07/09/1967	295	Trough	1017	Weak E flow on surface	-0.02
EL VERGER RACONS	38.9	0.03	08/09/1967	305	Trough	1017	Weak E flow on surface	-0.37
PEGO CONVENTO	38.8	-0.1	28/04/1969	232	Dynamic or Cold-core Low	1005	Low zonal index	-1.57
XALO	38.7	0	28/04/1969	223	&	&	&	&
VALL DE LAGUARD FONTILLES	38.8	-0.1	29/04/1969	253	Dynamic or Cold-core Low	1003	Low zonal index	-0.44
BENISSA AYUNTAMIENTO	38.7	0.05	06/10/1971	244	Advection from the E with DANA	1022	Central Europe A	-2.73
BENISSA CONVENTO	38.7	0.05	06/10/1971	249	&	&	&	&
BOLULLA	38.7	-0.1	06/10/1971	247	&	&	&	&
CALLOSA D'EN SARRIA TOSSAL DE SALOMÃ	38.7	-0.1	06/10/1971	253,7	&	&	&	&
EL VERGER RACONS	38.9	0.03	06/10/1971	218	&	&	&	&
TARBENA CH JUCAR POBLE DE DALT	38.7	-0.1	06/10/1971	210,7	&	&	&	&
VALL DE LAGUARD FONTILLES	38.8	-0.1	06/10/1971	237	&	&	&	&
XALO	38.7	0	06/10/1971	226,6	&	&	&	&
EL VERGER RACONS	38.9	0.03	30/11/1972	213	Trough	1007	Azores A	-0.36
PEGO CONVENTO	38.8	-0.1	22/03/1973	216	Advection from the E with DANA	1015	--------------	-2.56
TARBENA CH JUCAR POBLE DE DALT	38.7	-0.1	22/03/1973	205	&	&	&	&
ALICANTE/EL ALTET	38.3	-0.6	19/10/1982	235	Advection from the E with DANA	1014	Azores A	-1.13
SAN VICENTE DEL RASPEIG-ST	38.4	-0.5	19/10/1982	220	&	&	&	&
ALICANTE	38.4	-0.5	20/10/1982	233,1	Advection from the E with DANA	1011	NASH	-2.05

Meteorol. station	Lat.	Lon.	Date	mm	Synop. Situat.	hPa	Other synoptic characteristics	WeMOi
ALCALALI	38.8	-0	23/08/1983	217	Trough	1016	Weak E flow, Azores A extended to British Isles	-0.48
XALO	38.7	0	23/08/1983	220,8	&	&	&	&
LAGUNA DE LA MATA	38	-0.7	21/02/1985	220	Trough	1022	Advection from E on surface	-1.84
LAGUNA DE TORREVIEJA	38	-0.7	21/02/1985	220	&	&	&	&
EMBASSAMENT DE GUADALEST	38.7	-0.2	28/10/1985	210	Advection from the E with DANA	1015	British Isles A	-1.59
TARBENA CH JUCAR POBLE DE DALT	38.7	-0.1	28/10/1985	236,3	&	&	&	&
TORMOS	38.8	-0.1	28/10/1985	209	&	&	&	&
PEDREGUER	38.8	0.03	15/11/1985	373	Advection from the E	1019	Trough to the W Iberian Peninsula, Scandinavian A with bridge with Azores A	-2.12
PEGO CONVENTO	38.8	-0.1	15/11/1985	249	&	&	&	&
GATA DE GORGOS	38.8	0.09	16/11/1985	200	Advection from the E with DANA	1019	Scandinavian A with bridge towards Azores A	-1.76
TORMOS	38.8	-0.1	16/11/1985	259	&	&	&	&
PANTANO DE BENIARRES	38.8	-0.4	28/09/1986	208,6	Advection from the E with DANA	1024	Russian-Scandinavian A	-1.1
AGRES, FRUTOS EVA	38.8	-0.5	29/09/1986	233	Advection from the E with DANA	1024	British Isles A	-1.56
ALCALALI	38.8	-0	29/09/1986	220	&	&	&	&
ALCOI	38.7	-0.5	29/09/1986	251	&	&	&	&
ALCOI JUAN XXIII	38.7	-0.5	29/09/1986	350,1	&	&	&	&
ALMUDAINA	38.8	-0.4	29/09/1986	204	&	&	&	&
BANYERES DE MARIOLA	38.7	-0.7	29/09/1986	230	&	&	&	&
DENIA CENTRO CIUDAD	38.8	0.1	29/09/1986	217	&	&	&	&
PEDREGUER	38.8	0.03	29/09/1986	231	&	&	&	&
TARBENA CH JUCAR POBLE DE DALT	38.7	-0.1	29/09/1986	241,1	&	&	&	&
TORMOS	38.8	-0.1	29/09/1986	259	&	&	&	&
XALO	38.7	0	29/09/1986	223	&	&	&	&
AGRES, FRUTOS EVA	38.8	-0.5	30/09/1986	268	Advection from the E with DANA	1015	North Sea A	-2.04

Meteorol. station	Lat.	Lon.	Date	mm	Synop. Situat.	hPa	Other synoptic characteristics	WeMOi
CALLOSA D'EN SARRIA	38.6	-0.1	30/09/1986	200	&	&	&	&
CALLOSA D'EN SARRIA EL ALGAR	38.7	-0.1	30/09/1986	216,7	&	&	&	&
GORGA	38.7	-0.4	30/09/1986	232	&	&	&	&
TARBENA CH JUCAR POBLE DE DALT	38.7	-0.1	30/09/1986	218,2	&	&	&	&
COCENTAINA, BOMBERS	38.7	-0.5	03/11/1987	260	Advection from the E with DANA	1011	Bristish Isles A, rhombus pattern	-2.97
DENIA CENTRO CIUDAD	38.8	0.1	03/11/1987	377	&	&	&	&
DENIA, BOMBERS	38.8	0.1	03/11/1987	374,2	&	&	&	&
EL VERGER RACONS	38.9	0.03	03/11/1987	299	&	&	&	&
JAVEA-VIVEROS CHORRO	38.8	0.17	03/11/1987	217,9	&	&	&	&
PEGO CONVENTO	38.8	-0.1	03/11/1987	371,5	&	&	&	&
ORIHUELA 'LOS DESAMPARADOS'	38.1	-1	04/11/1987	316	Advection from the E with DANA	1015	Bristish Isles A	-2.84
PILAR DE LA HORADADA, LO MONTE	37.9	-0.8	04/11/1987	205	&	&	&	&
S. MIGUEL DE LAS SALINAS, CHS	38	-0.8	04/11/1987	265	&	&	&	&
SAN MIGUEL DE LAS SALINAS	38	-0.8	04/11/1987	265	&	&	&	&
SAN PEDRO DEL PINATAR, AYTO	37.8	-0.8	04/11/1987	210	&	&	&	&
ALCALALI	38.8	-0	30/09/1988	218	Trough	1015	Flows from NE on Surface, British Isles A	-1.29
BENISSA CONVENTO	38.7	0.05	30/09/1988	200	&	&	&	&
DENIA CENTRO CIUDAD	38.8	0.1	30/09/1988	200	&	&	&	&
GATA DE GORGOS	38.8	0.09	30/09/1988	206	&	&	&	&
TORMOS	38.8	-0.1	30/09/1988	258,5	&	&	&	&
XALO	38.7	0	30/09/1988	215	&	&	&	&
TORMOS	38.8	-0.1	18/03/1989	223	Advection from the E with DANA	1012	Azores A	-1
PILAR DE LA HORADADA, LO MONTE	37.9	-0.8	03/09/1989	210	Trough	1015	Azores A extended towards the N	-0.38
ABARAN (SIERRA DEL ORO)	38.2	-1.4	04/09/1989	205	Advection from the E	1015	Azores A extended towards British Isles	-0.69

Meteorol. station	Lat.	Lon.	Date	mm	Synop. Situat.	hPa	Other synoptic characteristics	WeMOi
					with DANA			
AGRES, FRUTOS EVA	38.8	-0.5	04/09/1989	200	&	&	&	&
ALMORADI, LAS MORERAS	38	-0.8	04/09/1989	212	&	&	&	&
LAGUNA DE LA MATA	38	-0.7	04/09/1989	250	&	&	&	&
LAGUNA DE TORREVIEJA	38	-0.7	04/09/1989	240	&	&	&	&
RICOTE (LA CALERA)	38.2	-1.4	04/09/1989	219	&	&	&	&
S.MIGUEL DE LAS SALINAS, CHS	38	-0.8	04/09/1989	228	&	&	&	&
SAN MIGUEL DE LAS SALINAS	38	-0.8	04/09/1989	228	&	&	&	&
TARBENA CH JUCAR POBLE DE DALT	38.7	-0.1	04/09/1989	255,6	&	&	&	&
EL VERGER RACONS	38.9	0.03	05/09/1989	242,3	Advection from the E with DANA	1015	Azores-British Isles A	-1.53
GATA DE GORGOS	38.8	0.09	05/09/1989	201	&	&	&	&
PEDREGUER	38.8	0.03	05/09/1989	206	&	&	&	&
GORGA	38.7	-0.4	07/09/1989	210	Advection from the E with DANA	1011	North Atlantic A	-2.1
CALLOSA D'EN SARRIA EL ALGAR	38.7	-0.1	03/05/1992	201	Advection from the NE with DANA	1014	Azores-British Isles A	-0.66
TARBENA CH JUCAR POBLE DE DALT	38.7	-0.1	03/05/1992	200	&	&	&	&
TORMOS	38.8	-0.1	03/05/1992	206	&	&	&	&
VALL DE LA GALLINERA-PATRO	38.8	-0.3	03/05/1992	244	&	&	&	&
TORMOS	38.8	-0.1	08/10/1992	218	Advection from the E with DANA	1014	British Isles A	-1.67
AGRES, FRUTOS EVA	38.8	-0.5	01/02/1993	203	Advection from the E with DANA	1023	Central Europe A	-2.78
ALMUDAINA	38.8	-0.4	01/02/1993	240,5	&	&	&	&
PEDREGUER	38.8	0.03	15/04/1994	266	Advection from the E with DANA	1012	Algeria low; A to the W of British Isles	-1.52
TORMOS	38.8	-0.1	10/09/1996	220	Advection from the E	1013	A to the W of British Isles	-1.88

Meteorol. station	Lat.	Lon.	Date	mm	Synop. Situat.	hPa	Other synoptic characteristics	WeMOi
					with DANA			
DENIA CENTRO CIUDAD	38.8	0.1	11/09/1996	420	Dynamic or Cold-core Low	1007	A to the W of British Isles	-1.71
CALLOSA D'EN SARRIA EL ALGAR	38.7	-0.1	08/04/1997	230	Advection from the E with DANA	1020	Central Europe-Scandinavia-Artic elongate A	-2.68
PEDREGUER	38.8	0.03	08/04/1997	239	&	&	&	&
ALICANTE	38.4	-0.5	30/09/1997	270,2	Advection from the E with DANA	1020	France-North Sea A	-1.07
SAN VICENTE DEL RASPEIG-ST	38.4	-0.5	30/09/1997	209,5	&	&	&	&
ALCALALI	38.8	-0	04/12/1997	230	Dynamic or Cold-core Low	1006	---------------	-1.68
JALON SOLANA	38.8	-0	04/12/1997	221	&	&	&	&
TARBENA C H JUCAR POBLE DE DALT	38.7	-0.1	04/12/1997	250,2	&	&	&	&
VALL DE LAGUARD FONTILLES	38.8	-0.1	04/12/1997	400	&	&	&	&
DENIA, BOMBERS	38.8	0.1	11/11/1999	330	Advection from the E with DANA	1016	British Isles A	-2.41
EL VERGER RACONS	38.9	0.03	11/11/1999	300	&	&	&	&
JAVEA AYUNTAMIENTO	38.8	0.17	11/11/1999	220	&	&	&	&
JAVEA-VIVEROS CHORRO	38.8	0.17	11/11/1999	240,8	&	&	&	&
PEDREGUER	38.8	0.03	11/11/1999	252	&	&	&	&
PEGO CONVENTO	38.8	-0.1	11/11/1999	237,7	&	&	&	&
DENIA CENTRO CIUDAD	38.8	0.1	23/10/2000	220	Advection from the E with DANA	1018	Azores A with bridge with Central Europe A	-2.41
EL VERGER RACONS	38.9	0.03	02/04/2002	230	Trough	1007	Algeria low, NASH	-1.29
PEGO CONVENTO	38.8	-0.1	06/05/2002	251	Dynamic or Cold-core Low	1012	Azores A with bridge with Scandinavian A, flow from the E on surface	-2.1
VALL DE LAGUARD FONTILLES	38.8	-0.1	07/05/2002	300	Dynamic or Cold-core Low	1002	A to the W of British Isles with bridge with Scandinavian A, flow from the E on surface	-2.47

Meteorol. station	Lat.	Lon.	Date	mm	Synop. Situat.	hPa	Other synoptic characteristics	WeMOi
AGRES, FRUTOS EVA	38.8	-0.5	15/04/2003	200	Trough	1010	Russian-Scandinavian A, Algeria low	-2.51
VALL DE LA GALLINERA-PATRO	38.8	-0.3	15/04/2003	210	&	&	&	&
VALL DE LAGUARD FONTILLES	38.8	-0.1	15/04/2003	222,5	&	&	&	&
DENIA CENTRO CIUDAD	38.8	0.1	11/10/2007	210	Advection from the E with DANA	1017	A over European mid-latitudes	-1.59
JALON SOLANA	38.8	-0	11/10/2007	231,9	&	&	&	&
VALL DE LAGUARD FONTILLES	38.8	-0.1	11/10/2007	371,2	&	&	&	&
ALTEA, IVIA	38.6	-0.1	12/10/2007	204,8	Advection from the E with DANA	1017	British Isles A, rhombus pattern	-0.98
BOLULLA	38.7	-0.1	12/10/2007	222	&	&	&	&
DENIA-GATA, IVIA	38.8	0.08	12/10/2007	228,2	&	&	&	&
GATA DE GORGOS	38.8	0.09	12/10/2007	258,9	&	&	&	&
ONDARA, IVIA	38.8	0.01	12/10/2007	218	&	&	&	&
PANTANO DE BENIARRES	38.8	-0.4	12/10/2007	230	&	&	&	&
PEDREGUER	38.8	0.03	12/10/2007	293	&	&	&	&
PLANES, IVIA	38.8	-0.4	12/10/2007	246,2	&	&	&	&
TARBENA C H JUCAR POBLE DE DALT	38.7	-0.1	12/10/2007	227	&	&	&	&
VALL DE LA GALLINERA-PATRO	38.8	-0.3	12/10/2007	333	&	&	&	&
VALL DE LA GALLINERA-PATRO	38.8	-0.3	08/10/2008	205	Trough	1015	Azores A	-0.26
PANTANO DE BENIARRES	38.8	-0.4	10/10/2008	234,6	Advection from the E	1023	Dynamic cold-core low over Morocco, Central Europe A	-3.03
ALMORADI C H SEGURA	38.1	-0.8	28/09/2009	236	Advection from the E with DANA	1018	British Isles A, rhombus pattern	-1.2
PANTANO DE BENIARRES	38.8	-0.4	28/09/2009	202,2	&	&	&	&
TARBENA C H JUCAR POBLE DE DALT	38.7	-0.1	25/01/2010	236	Trough	1022	Flows from the E on surface, Argelia low, high zonal index	-1.8
HUERCAL OVERA	37.4	-1.9	28/09/2012	243,8	Dynamic or Cold-core Low	1008	Azores A with bridge with Russian A	-1.71

Meteorol. station	Lat.	Lon.	Date	mm	Synop. Situat.	hPa	Other synoptic characteristics	WeMOi
PUERTO LUMBRERAS	37.6	-1.8	28/09/2012	204,2	&	&	&	&
PANTANO DE BENIARRES	38.8	-0.4	11/11/2012	220	Dynamic or Cold-core Low	1009	Azores A	-0.57
VALL DE LAGUARD FONTILLES	38.8	-0.1	11/11/2012	230	&	&	&	&
ALMUDAINA	38.8	-0.4	18/12/2016	255	Advection from the E with DANA	1024	NASH with bridge with British Isles-France-Central Europe A	-2.31
PANTANO DE BENIARRES	38.8	-0.4	18/12/2016	200,2	&	&	&	&
TORRE PACHECO, TORRE BLANCA	37.8	-0.9	18/12/2016	221,3	&	&	&	&
TORREPACHECO (TORRE BLANCA)	37.8	-0.9	18/12/2016	202	&	&	&	&
PANTANO DE BENIARRES	38.8	-0.4	19/12/2016	201,5	Dynamic or Cold-core Low	1011	NASH with bridge with Central Europe A	-2.5
PLANES, IVIA	38.8	-0.4	19/12/2016	316,1	&	&	&	&
VALL DE LAGUARD FONTILLES	38.8	-0.1	19/12/2016	213	&	&	&	&
MULA (EMB. DE LA CIERVA)	38.1	-1.5	19/01/2017	330	Dynamic or Cold-core Low	1012	Central Europe A	-2.44
BOLULLA	38.7	-0.1	21/01/2017	217	Dynamic or Cold-core Low	1011	Azores A	-2.04
CALLOSA D'EN SARRIA TOSSAL DE SALOMÃ	38.7	-0.1	21/01/2017	210,8	&	&	&	&
TARBENA CH JUCAR POBLE DE DALT	38.7	-0.1	21/01/2017	338	&	&	&	&

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BEFORE, DURING AND AFTER THE DANA OF SEPTEMBER 2019 IN THE REGION OF MURCIA (SPAIN), AS REPORTED IN THE WRITTEN PRESS

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ABSTRACT. In September 2019 a DANA affected the Southeast of Spain with a special impact on the Segura Basin and the Region of Murcia. Heavy rainfall caused widespread flooding, very serious damage and generally affected the whole population. The main objective of this work was to analyse this episode through a follow-up of all the news published in two regional newspapers, La Verdad and La Opinión. To this end, a methodological proposal was made to classify the news according to: the typology of the subject, the relevance of the DANA in terms of frequency and how the news developed. A total of 816 news articles covering 52 days were studied and grouped into 26 subjects. The issues that aroused most interest, were those relating to the solidarity offered and aid provided to those affected, the effects on the Mar Menor (a nearby coastal lagoon); visits by politicians, personalities and their statements; solutions and mitigation measures; evacuations, rescues and displacements. The database analysed allowed us to organise the information into different aspects and in sequence: (i) prevention tasks and warnings prior to the materialisation of a risk situation; (ii) rescues, relief and assistance to persons, and (iii) response, rehabilitation and reconstruction.

Antes, durante y después de la DANA de septiembre de 2019 en la región de Murcia (España), según se informó en la prensa escrita.

RESUMEN. En el mes de septiembre de 2019 un DANA afectó el sureste español con un impacto especial en la cuenca del Segura y en la región de Murcia. Las fuertes lluvias provocaron inundaciones generalizadas, daños muy graves y afectaron en general a toda la población. El objetivo principal de este trabajo fue analizar este episodio a través de un seguimiento de todas las noticias publicadas en dos periódicos regionales, La Verdad y La Opinión. Para ello, se realizó una propuesta metodológica para clasificar las noticias según: la tipología del tema, la relevancia de la DANA en términos de frecuencia y cómo se desarrolló la noticia. Se estudiaron un total de 816 artículos informativos que abarcaron 52 días y se agruparon en 26 temas. Los temas que más interés despertaron fueron los relacionados con la solidaridad ofrecida y la ayuda brindada a los afectados, los efectos en el Mar Menor, las visitas de políticos, personalidades y sus declaraciones, las soluciones y medidas de mitigación, las evacuaciones, rescates y desplazamientos. La base de datos analizada permitió organizar la información en diferentes aspectos y en secuencia: (i) tareas de prevención y alertas previas a la materialización de una situación de riesgo; (ii) rescates, socorro y asistencia a las personas, y (iii) respuesta, rehabilitación y reconstrucción.

Key words: DANA, floods, written press, south-eastern Spain.

Palabras clave: DANA, inundaciones, prensa escrita, sureste de España.

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1. Introduction

On September 12th and 13th, a "Cutt-of-low" or "DANA" (isolated high-altitude depression) struck the Southeast of Spain, affecting the Segura River Basin and the Region of Murcia very intensely. This work analyses the effects of the torrential rains, and the floods that caused significant damage to several areas of the Region of Murcia, based on the news published in the two most widely read local newspapers: La Verdad (founded in 1903) and La Opinión (founded in 1988). In 2019 the number of readers of La Verdad was estimated at 121,000 and those of La Opinión at 57,000.

Seventy-two hours before this weather event, the 'Meteoalerta' service of AEMET (State Meteorological Agency) began publishing warnings about the possible severity of this event, information that was relayed by the media. As the extreme weather unfurled, news on the same increased, especially in the immediate days after, although the effects were still being felt until long after. It was therefore considered appropriate to extend the observation period from the 10th of September (2 days before the DANA) to the 31st of October (48 days later), when related news was already scarce or non-existent.

According to Olcina Cantos *et al.* (2004) "The daily press is a useful source for the study of extraordinary natural episodes, since newspapers provide information on the socio-territorial consequences of the same, situates the episode chronologically, identifies the effects in a region and provides graphic documents of the consequences". Newspapers have been widely used as a source of information similar studies in Spain, although following different approaches. Table 1 shows some of these studies showing greater thematic affinity with this research.

Table 1. Some of the publications related with weather and floods using information from the written press.

Theme	Place/theme	Author
Climate risks	Catalonia	Llasat-Botija *et al.,* 2006
	Western Mediterranean	Llasat-Botija *et al.,* 2007
Climate-weather aspects	Gran Canaria	Mayer Suarez, 1999
	Galicia	García Martínez and Martín Ezpeleta, 2000
	Basque Country	Hernández Valera *et al.,* 2003
	Catalonia	Llasat *et al.,* 2009
	Iberian Peninsula	Domínguez-Castro *et al.,* 2015
	Palma de Mallorca	Torrens Calleja *et al.,* 2016
	Extreme weather events	Lopera Pareja, 2017
	Weather and climate	Olcina Cantos, 2005
Floods	1978 Flood in the Lower Segura	Calvo García-Tornel *et al.,* 2001
	Las Palmas de Gran Canaria	Mayer Suarez, 2002
	Flooding in Alicante	Olcina Cantos *et al.,* 2004
	Navarrese Cantabrian Valleys	Pejenaute Goñi, 2008
	Province of Cadiz	Cuello Gijón, 2010
	Rio Rojo, Manitoba, Canadá	Rashid, 2011
	1948 Flood in the Segura Basin	Pérez Morales and Gil Guirado, 2012
	Historic floods in Texas	Melinda, 2015
	Floods in Spain 1995-2014	Gutiérrez Abril, 2016
	Historic floods in France	Lang *et al*., 2016
	Floods in Seville, 20th century	León González-Mazón, 2017
	Flash floods in Great Britain	Archer and Fowler, 2018
	Flash floods in Great Britain	Archer *et al.,* 2019
	Floods as an educational resource	Cuello Gijón, 2018
	Flood chronology (14-20 century)	Barriendos *et al.,* 2019
	Mediterranean coast Spain (1960-2015)	Gil Guirado *et al.,* 2019
	Flooding in Vetania (Argentina)	Ortuño Cano *et al.,* 2019
	Danube floods from1012 to the present	Prohaska *et al.,* 2019

In the above works, although the press seems to play a valuable role in identifying flood episodes, none of them tried to track a particular episode on day-to-day basis, as we have done in this work.

The main objective was to classify the news in the press related to a flood episode, specifically the one that took place in September 2019 in the Region of Murcia. Through frequency indicators related to the subject in the news and its chronological development, a sequence of environmental and social-related matters can be reconstructed that shows, among other things: the importance of the episode in its physical properties and derived socio-economic impacts; the attitudes and response strategies of the different institutions involved in risk management and, subsequently, the catastrophe itself; aspects that highlight the overall vulnerability of the affected system and ultimately increase the risk; the perception and type of measures proposed or adopted by local administrators of to alleviate the effects of the catastrophe. Finally, given the possible bias of the source of information, the news articles in two different newspapers dealing with the episode were compared in order to minimise this effect.

1.1. Brief analysis of the DANA and the area of affection

In order to have a more complete context of what happened with the DANA of September 2019 in the Region of Murcia, and thus be able to better assess its media impact, the following is a brief analysis of the atmospheric situation and the areas most affected by the intense rains.

The DANA took place as a result of the movement of a series of low pressures from the north to the south from the 11th (and subsequently inversely) combined with the entry of humidity from the Mediterranean on the 12th, which led to an explosive synoptic situation in the Spanish Mediterranean coast, mainly in the triangle formed from the south of the Region of Murcia, the eastern half of Albacete and the province of Valencia. This flow of humidity, together with the dominant instability, resulted in torrential rainfall which has been catalogued as historic in many places on the east of the Iberian Peninsula, and in particular in the Region of Murcia (Fig. 1), as well as a very notable sea storm, with waves which reached 4 metres. The most virulent part of the storm occurred from the early morning of the 12th to midday of the 13th. Several convective fronts moved from the north to the south, leaving torrential rain in their wake.

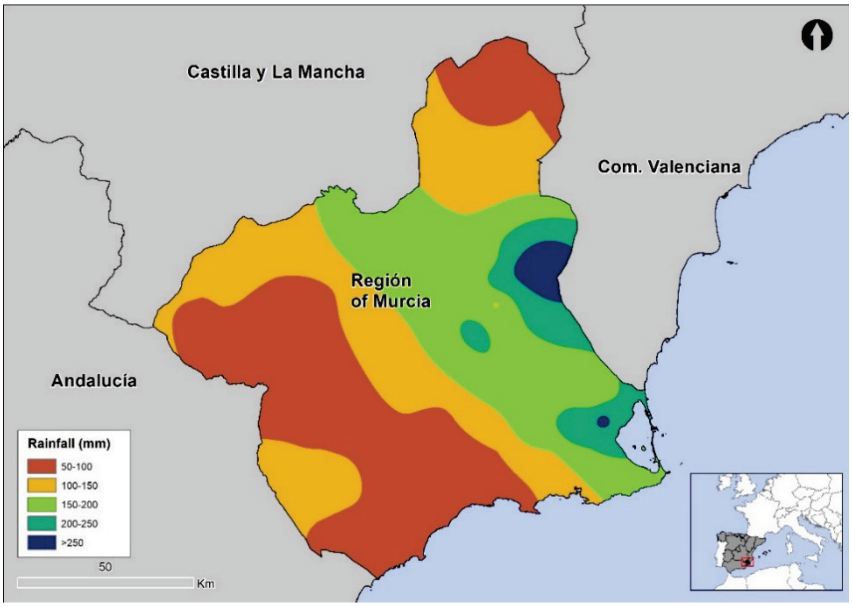

Figure 1. Precipitation recorded in the DANA episode in the Region of Murcia during September 12-13. Source: Own elaboration according to AEMET data.

The episode left historical records, with rainfall falling in 2 days that equal or exceed the average annual rainfall in many parts of the region: Molina de Segura 374 litres, La Manga del Mar Menor 335 litres and San Javier 335 litres. In the Region of Murcia, the area most affected was the Vega Media del Segura and the Campo de Cartagena-Mar Menor, especially in the municipalities of Los Alcázares and San Javier (Fig. 2) on the slopes of the Mar Menor, with rainfall of 146 mm in one hour in La Manga del Mar Menor or 109 mm in San Javier. In addition, the concentration of rainfall in two events with a time lapse of just one day aggravated the situation.

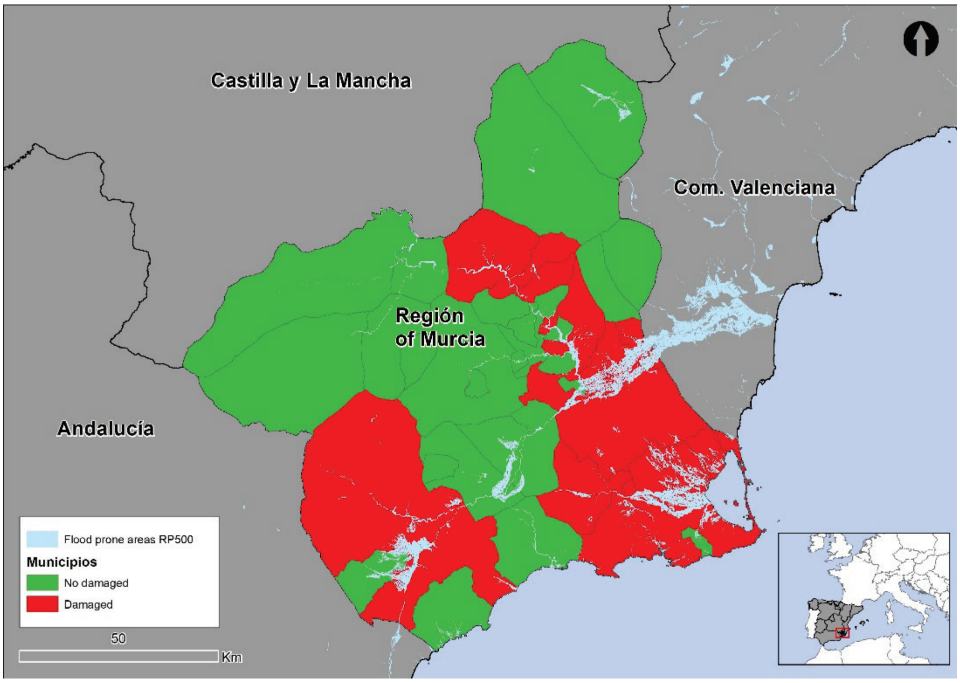

Figure 2. Municipalities affected by the DANA episode in the Region of Murcia. Source: Own elaboration according to data obtained from the press analysed.

The density of built up area on the coast, the occupation of watercourses (by housing, industry, crops, etc.), the increase in infrastructure, the elimination of soil conservation practices due to the installation of new "industrial" agriculture, and the low slope of the territory, meant that the DANA episode caused exceptional material and economic damage. It is worth noting, as can be seen in Figure 2, that the areas with the greatest impact coincide with the areas of flooding for a return period of 500 years.

2. Methods and sources

Although the DANA also affected much of the Lower Segura in the province of Alicante, our study focused specifically on the province of Murcia, which is the range of distribution of the newspapers analysed.

The newspapers herein, not only related the daily events and numerous testimonies, but also provided chronicles, reports, opinion articles, editorials and images of what happened, from which it has been possible to obtain a very valuable set of data that present different points of view (descriptive, personal, technical, political, economic or scientific). We are aware of the advantages and disadvantage of press reports and occasionally sensationalist nature but, despite this, we consider it an important source of information, as long as that information is systematically and thoroughly processed and filtered.

The news collected by us, referring solely to the DANA episode and its consequences, differed depending on the day on it was published (before, during and after the event) and some items dealt with various aspects at the same time. The news items were grouped into 26 topics, including an “other” section, which included news that did not fit into our selected categories, which are described below:

1. Warnings and prevention
2. Cancellation of activities
3. Resumption of activities
4. Climate-weather aspects
5. Hydrological aspects
6. State of riverbeds, banks and beaches
7. Flooded areas and places
8. Management of reservoirs
9. Evacuations, rescues and displacements
10. Harmful effects on the population
11. Damage to property
12. Damage to infrastructure
13. Damage to agriculture, livestock and fisheries
14. Damage to industry and other property
15. Effects on the Mar Menor Lagoon
16. Solidarity with and aid provided to those affected
17. Emergency management
18. Damage and loss assessment
19. Declaration of a disaster area
20. Responsibilities
21. Compensation and payments
22. Visits by politicians and personalities, and their statements
23. Repairs and cleaning up
24. Causes of flooding
25. Solutions and measures to be taken
26. Other.

Overall, a total of 816 news articles were analysed, of which 467 were taken from the newspaper La Verdad and 349 from La Opinión. These numbers include opinion articles, jokes and cartoons and similar (Table 2).

Table 2. News analysed and extracted from the two regional newspapers.

Type of news	La Verdad	La Opinión	TOTAL
Varied	435	333	768
Opinion piece	18	13	31
Joke/cartoon	14	3	17
TOTAL	467	349	816

3. Results

3.1. Number of news items per day

The number of articles related with the DANA varied as time progressed (Fig. 3). The highest number of news articles appeared between the 13th and 17th of September, since the heaviest rainfall was recorded on the 12nd and 13th of the same month. From the 18th of September onwards, the frequency of related news gradually diminished until about the 26th. From that time until the 10th of October, the average number of related articles per newspaper was five, dropping to two or three until the 26th of October, almost disappearing a few days later.

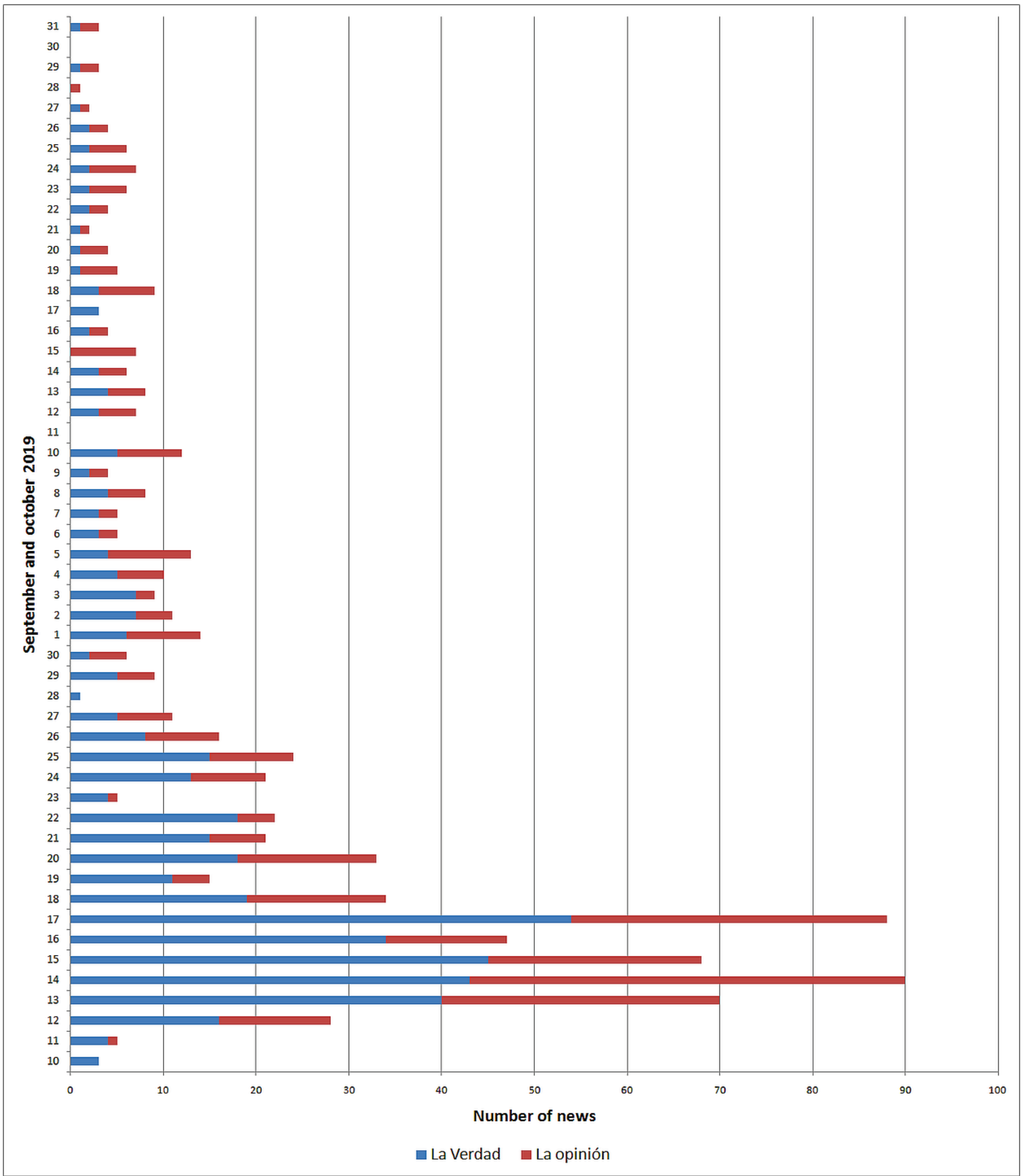

Figure 3. Number of daily news items published on the DANA in the two newspapers analysed between September 10th and October 31st.

The number of articles in La Opinión was usually lower than in La Verdad, although on some days an almost equal number was published and even, at times, was greater in La Opinión. On the 13th of September both newspapers published an almost equal number of news articles, but La Verdad published more DANA-related news in September, while the memory of the episode was more evident in La Opinión in October.

3.2. Thematic analysis of the news

The number of news items differed depending on the subject and the newspaper (Fig. 4). Overall, the issues that were most addressed were solidarity of people and the aid provided to those affected (Topic 16), the effects on the Mar Menor Lagoon (Topic 15), followed by visits by politicians, personalities and their declarations (topic 22), solutions and measures (topic 25), and evacuations, rescues and displacements (topic 9). As for media differentiation, La Verdad focused more on solidarity, visits by politicians and infrastructure damage; while La Opinión did so on the effects of the DANA on the Mar Menor. There were little differences between the two newspapers in the extent to which they treated evacuations and rescues, damage assessment or solutions and measures alike.

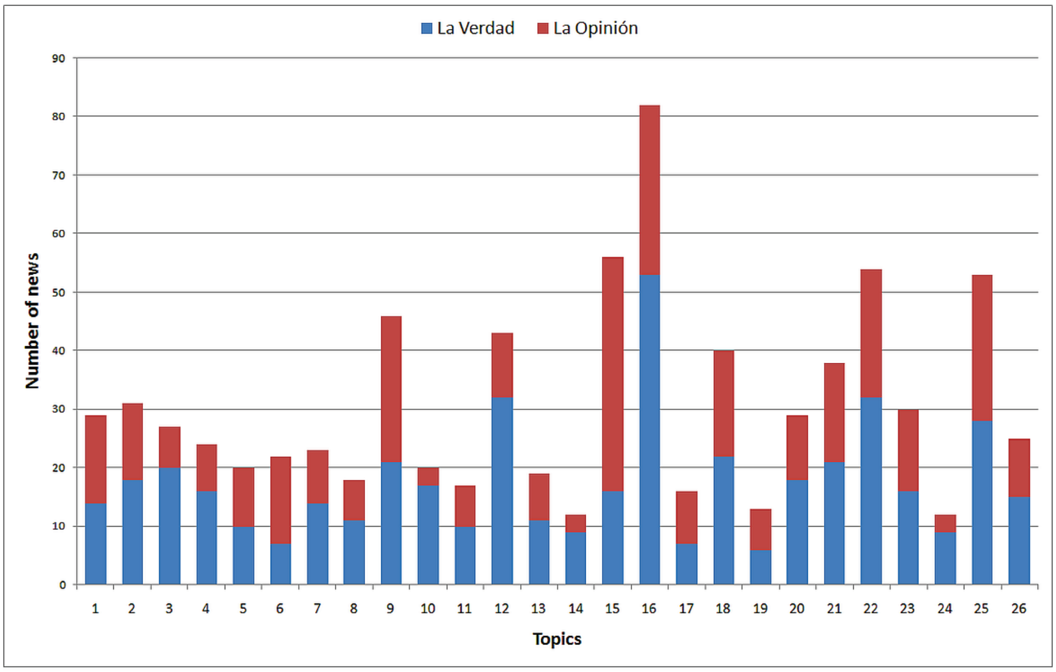

Figure 4. Number of news items by topic in the two newspapers analysed. See the methods and sources section for an explanation of the topic numbers.

The following is a summary of the news classified into topics:

*1.- Warnings and prevention***.** The news items concerning warnings and prevention were obviously more numerous in the days leading up to the episode of DANA (10th, 11th and 12th), based on the warnings of AEMET. In both newspapers, the number of items was similar, with a similar content but different headlines. The news referred to the "maximum" alert level and that the DANA or cold drop would affect the whole region with rainfall of 200 l/m^2. It should be noted that this was the first time that a red alert had been decreed for the whole region. Photographs appeared of teams urgently cleaning "ramblas" (dry river beds, intended to channel flood waters) in different parts of the region. People were advised not to use their cars, take extreme precautions and stockpile water, food and medicines. Sports facilities were refurbished to accommodate evacuees. On the 14th, reeds were still being removed against the clock from below the bridges of the city of Murcia to prevent the river from overflowing. On the 17th, after the extreme weather episode, prevention notices were issued by health authorities, urging to follow the advice of local council as regard the consumption of water and asking people to notify the authorities if they found animal carcasses.

2.- Suspension of activities. In anticipation of the red alert, a decree suspending activities was emitted on the 12th. Classes for all education levels were suspended and "EBAU" (university entrance examinations) were formally postponed. Fairs (common at that time of the year) were closed and all scheduled activities were suspended. In the municipality of Molina de Segura the local fair was postponed. In La Manga del Mar Menor a regatta was postponed, as well as other sporting events, and two cruise ships cancelled their stopovers in Cartagena. In Lorca, the Almenara shopping centre was closed and in different places of the province, industries and shops interrupted their activities. Because broken railway lines, all rail traffic connecting Murcia with Madrid, Barcelona and Cartagena was suspended. The law courts and other legal services of Murcia, Molina, San Javier and Mula were closed. Flooding also caused the closing of Corvera International Airport and the AP-7 motorway, while another 55 roads were cut. For several days afterwards, many schoolchildren (especially in Los Alcázares) could not return to class, the rail network was still awaiting repair and numerous roads were still not open to traffic. Eight days after the DANA the inhabitants of Los Alcázares still had no drinking water.

3.- Resumption of activities. News on the resumption of activities ran from the 15th of September to the 20th of October, depending on the type of activity or infrastructure affected. Classes resumed in schools on different dates, depending on the degree of damage. The airport reopened and, in Los Arcos hospital (San Javier), flooded basements and operating theatres were disinfected. On September 20, rail traffic was restored between Murcia and Albacete, on October 10 with Alicante, on October 16 with Cartagena but not until October 20 with Águilas.

4.- Climate-weather aspects. The climate-weather data offered by the press varied. Data from official sources included radar images from AEMET on how the DANA was developing, and maps of the rainfall recorded in different locations in the region. Precipitation records were cited for the episode: 335 mm/m^2 in Molina de Segura, 264 in Torre Pacheco or 241 in Cieza; or 32 l/m^2 fallen in 10 minutes in La Manga. Some of the headlines were very eloquent: "The Mediterranean hurricane", "There is no precedent for the water that has fallen", "The rain that has fallen equals to the rainfall of an entire year", "Floods break many records", "The most photographed and recorded [storm] in history", or "The worst flood of the last 70 years in the Region". The magnitude of this episode caused the Ministry of the Environment to call for declare a "climate emergency."

*5.- Hydrological aspects***.** From a hydrological point of view, the press ran reports on overflowing "ramblas" carrying away everything in their path, such as those of Miranda in the area known as Campo de Cartagena, or those of Espinardo and Churra; and flooding of the Segura river in the municipalities of Cieza, Archena, Molina de Segura and in numerous villages of the municipality of Murcia. The amount of rain falling in the Segura basin amounted to 2800 hm^3 (more than twice the capacity of all its reservoirs) and it is estimated that the Segura discharged the equivalent of 20,500 Olympic swimming pools into the sea in four days (51 hm^3). Other noteworthy stories focused on the Santomera reservoir, which at one point held 20 hm^3, throwing into doubt its structural strength. On the 12th of September, a map of the 20 flood-sensitive areas in the region was published, but in light of the floods, and after verifying that this document was not true to reality, a new map rectifying the information was published on the 25th of September.

6.- State of riverbeds, banks and beaches. Many of the news reports were related to the state of the rivers and ramblas, criticizing the Segura Hydrographic Confederation (CHS in Spanish) for their negligence in cleaning water channels, or demanding their urgent cleaning, since this was cited as the main cause of the flooding. The images published of bridges blocked by reeds in the municipalities of Molina and Murcia were very illustrative. With regard to the beaches, in addition to their poor state, especially those surrounding the Mar Menor and in La Manga, three other facts were attributed to the DANA: (i) a reservoir built to retain mining waste in Portman overflowed (September 15); (ii) dead tuna were washed up on the beaches of La Manga because of offshore fish farms breaking (15 September); (iii) extremely hazardous mining waste entered the southern part of the Mar Menor through the ramblas (5 October); and (iv) an enormous amount of dead fish appeared in the municipality of San Pedro del Pinatar in the northern part of the lagoon (October 13 and successive days).

7.- Flooded areas and places. The most striking images correspond to September 13, highlighting the extensive areas and places flooded in the "huerta" (area dedicated to growing fruit and vegetables) in the municipalities of Molina del Segura, Archena, Alguazas and several villages near Murcia. On the 14th of September, images of Los Alcázares, known as ground zero, were published (Fig. 5).

On September 14th, a map was also published with the effects of the storm in various places in the region, especially in the Vega del Segura from Cieza to Alicante, suburbs of Murcia city bordering the Segura river, Santomera and Beniel, Lorca, Cartagena, and the municipalities bordering the Mar Menor: Fuente Álamo, Torre Pacheco, San Pedro del Pinatar, San Javier and Los Alcázares.

Figure 5. Aerial view of the effects of DANA on Los Alcázares and the Mar Menor. Source: La Verdad, 14th Sept 2019.

*8.- Management of reservoirs***.** During the DANA, the reservoir in Santomera became the centre of attention, since this was the first time in its history that floodgates had to be opened and the water level lowered due to it reaching the limit of its capacity as a result of the waters collected from the ramblas and, in particular, the water coming from the ruptured canal of the Tagus-Segura transfer system. Other reservoirs that were closely watched were those at Camarillas (at the head of the Segura Basin), which also reached the limit of its capacity, or the one at Valdeinfierno (at the head of the Guadalentín river), which drains into the reservoir at Puentes (located downstream).

In general, the role of these infrastructures and their management were called into question from different points of view. The CHS highly placed a high value on the expensive Anti-flood Plan (Ezcurra, 2007) and its president mentioned that the Santomera dam had saved lives. Others felt that the flood prevention works had led them to believe that the risk of flooding had been solved forever, which clearly was not the case. The CHS president also replied to people who claimed that there was a need for more reservoirs near the flooded villages and in the Vega Baja, mentioning that their construction was impossible in these places.

9.- Evacuations, rescues and displacements. Because of the danger of the Santomera reservoir overflowing or even breaking, several villages downstream of the reservoir had to be evacuated (e.g. El Siscar and La Matanza), although other towns had to be evacuated, too, including Cieza, Blanca, Molina de Segura, Alguazas, Abanilla, Fortuna, some districts of Murcia (El Raal, Alquerías, Zeneta and Santa Cruz), Los Alcázares, Torre Pacheco; as well as the campsites of the rambla de la Azohía (Mazarrón) and the Villas Caravan site near La Manga. People trapped in their vehicles had to be rescued, some by helicopter or tractor. Hundreds of people were trapped in their homes without being able to leave. According to Civil Protection data, more than 2000 people were evacuated and more than 1000 rescues were carried out, of which a hundred were by air.

10.- Harmful effects on the population. Fortunately, in the Region of Murcia, there were no fatal casualties, but the economic damage was extensive. Thousands of people were affected, especially in Los Alcázares. Taking advantage of the situation, homes, shops and the post office of Los Alcázares were raided or damaged. Water and electricity were cut off in many places.

11.- Damage to property. Some of the newspaper headlines speak for themselves: 15 boats moored in the Algameca of Cartagena were lost in the Mediterranean; 25 rubbish containers were hauled out of the Mar Menor (4200 t of waste); in Los Alcázares 14,000 homes, along with infrastructure and companies, were affected by the DANA, and 400 vehicles were damaged; Cartagena city council took away180 tonnes of household items in Los Nietos and Los Urrutias (south of the Mar Menor). Other headlines such as “We’ve lost everything that was in the house” and “Mud up to the eyeballs” reflect people’s experiences.

12.- Damage to infrastructure. Damage to infrastructure was widespread and we only mention: damage to the railway lines linking Murcia with Alicante, Albacete, Cartagena and Lorca, and also 100 m of the new high-velocity track being built; the infrastructure carrying the water of the Tagus-Segura transfer channel system fractured; dozens of roads throughout the region were damaged, and traffic was prohibited; rupture of a dam and mining depot in Portman; damage to a desalination plant and a water treatment plant; destruction of promenades; the Tomás Maestre pleasure harbour in La Manga was affected by the rising sea level; destruction of the Murcia-Rio garden project in the city of Murcia; fallen masonry in the Santa Florentina market in Cartagena; a sinkhole appeared in Juan de Borbón Avenue in Murcia; and damage to countless irrigation infrastructures.

*13.- Damage to agriculture, livestock and fisheries***.** Losses in agriculture and collateral damage featured regularly in the information provided and related declarations by representatives of agricultural associations, farmers and even by the Minister of Agriculture, who described vegetables, grapes, rice and citrus fruits as being among the most affected crops; and some farmers from Jumilla said that the harvest had been seriously threatened and that vineyards, olive trees and almond trees could not be recovered, and that 150,000 hectares were affected by the rupture of the hydraulic infrastructure. Job losses in the countryside were mentioned, as was the intention to provide a temporary subsidy for day-labourers who were out of work. Farmers advocated that the European Commission activate the Solidarity Fund to deal with damage in the production sector. Regarding livestock, 1500 animals were estimated to have died only in the Campo de Cartagena. The storm led to tuna escaping from a fish farm, with 1300 dead tuna washing up on the beaches of La Manga and south of Alicante. Days after the DANA, dead fish and seahorses appeared in the Mar Menor and a month later (October 13th) thousands of fish and crustaceans were seen to have died in the northern sector of the Mar Menor. ANSE, a nature protection association and the fishermen of San Pedro del Pinatar (the municipality most affected) proposed a one-year paid ban on fishing.

14.- Damage to industry and the services sector. The greatest damage was to the tourist sector, with the cancellation of reservations in hotels and apartments in the Mar Menor, the non-arrival of tourists from cruise ships scheduled to call in Cartagena or the closing for several weeks of golf courses in the Campo de Cartagena-Mar Menor area. The significant losses to the Region's cultural heritage sites should also be mentioned.

15.- Effects on the Mar Menor lagoon. News on the Mar Menor was abundant during the days that the DANA occurred and continued until the end of October because of the lagoon’s poor environmental state after the episode. However, only items related to the DANA itself have been collected here. Most reports mentioned the sediments that entered the lagoon, turning it brown. The Sentinel satellite image of September 13th, 2019 (Fig. 6) is very eloquent in this respect. According to a scientific report published in La Verdad on November 14, 2019, the sediments that entered the lagoon in the DANA episode were estimated at 100,000 tonnes, which contained between 500 and 1000 t of nitrates, more than 100 t of phosphates and 35 t of ammonium. In addition, the inflow of fresh water, according to some experts, would cause a decrease in salinity with unpredictable effects on flora and fauna. Both factors (sediments and fresh water) would have contributed to the massive death of fish and crustaceans that occurred days later. The DANA aggravated the poor health of the Mar Menor and numerous news articles were dedicated to this, and especially to the individuals and organisation that, to this day, to propose actions for its improvement. The mass demonstrations that took place in Murcia and Cartagena in defence of the Mar Menor, which were also echoed by the press, should be mentioned.

16.- Solidarity and aid provided to those affected. People’s solidarity was evident from the day of the episode up until the end of October. Thousands of volunteers who, either on buses that were chartered for free or by their own means, travelled to Los Alcázares, Torre Pacheco, San Javier, Los Nietos or Molina de Segura, to assist in the cleaning of houses, schools, churches and streets. Banks made donations and opened accounts to help in this process, provided free loans before official aid and compensation were provided, and established special credit lines for farmers and families, as well as zero-cost lending to small businesses and the self-employed. Local folklore groups, “Peñas Huertanas”, offered to cook for the victims; Jesús Abandonado (a charitable organisation, provided food and accommodation; the University of Murcia organised a collection to provide essential; the inhabitants of nearby Alcantarilla collected 8 t of food, blankets and clothes; there were campaigns to collect school material and textbooks; numerous private individuals and companies in Los Alcázares gave furniture and other items; another charity, Caritas, offered a variety of goods and services, including a truckload of furniture; concerts, music galas and meals, while sporting events were organized for the benefit of the affected; the Los Alcázares City Council reduced property taxes (IBI) and lowered the cost construction permits. Cartagena paid the water bills to those affected by the DANA. Hundreds of animals were also rescued from the waters by volunteers and animal protection associations.

Figure 6. Image of the Mar Menor on 13th of September 2019. Note the sediments entering the Mar Menor and the flooded towns and villages. Source: Sentinel. 2.

17.- Emergency management. In addition to personnel from state agencies (CHS, AEMET, UME), staff from regional agencies and companies, the Red Cross, public health official, local police, municipal civil protection services, firefighters and forest protection brigades also participated in emergency relief. Level 2 of the Special Emergency Civil Protection Plan was activated on 12th September, and was lowered to level 1on the 19th before being deactivated on October 4th. Municipal Emergency Plans had to be activated in Águilas, Lorca, Los Alcázares, Mazarrón, Molina de Segura, Murcia, Puerto Lumbreras, San Javier and San Pedro del Pinatar. According to regional government sources, the September DANA triggered 8572 calls to the emergency phone number (112) (one every 10 seconds), of which 1965 were requests for information; 1697 were about floodwater in basements and lower floors, 492 about removing obstacles blocking public roads and 460 requesting rescue from trapped vehicles or their homes (60 of which involved air rescues. The municipality with the most incidents treated was Murcia city (1336), followed by Los Alcázares (1073), Cartagena (467) and San Javier (464). The Defence Ministry deployed almost 900 military personnel and a hundred vehicles in the province.

18.- Damage and loss assessment. Two days after the DANA, estimates of the damage begun to be made and, in Los Alcázares alone, losses amounted to more than 100 million euros. Almost every day new figures appeared in the press, but until October there was no realistic evaluation of the damage. The Insurance Compensation Consortium considered 12,000 homes, 5000 vehicles and 113,300 hectares of crops had been affected by flooding. Losses in agriculture led to some 1720 declarations of damage as a result of landslides, gullies, cracked roads, broken fences, and damaged factories or greenhouses. The losses in the agricultural sector amounted to 125 million euros, which includes damage to production infrastructures (52.4 million euros), losses in crop production (23.3 million euros), livestock and farmed fish (25.0 million euros), damage to rural roads and municipally owned facilities (18.5 million euros) and public infrastructure related with the environment and water purification (5.6 million euros). In addition, private assets were calculated at 238 million euros, municipal facilities 145 million euros, state infrastructure 60 million euros and those of province-owned at 46.5 million euros. The overall damage assessment was 590 million euros. Los Alcázares suffered by far the most damage compared with the rest of the affected municipalities, followed by San Pedro del Pinatar, Torre Pacheco and the city of Murcia.

19.- Declaration of a disaster area. The request that the affected municipalities be declared a catastrophic zone was unanimous. The voices that requested the same were all the political parties, the president of the autonomous community, the regional assembly and the town councils of Los Alcázares, San Javier, San Pedro del Pinar, Abarán, Beniel, Lorquí, Mazarrón, Torre Pacheco, Cartagena and Jumilla. In addition, the regional government demanded that the Spanish state ask for the European contingency fund be applied to help cover the losses.

20.- Responsibilities. The harsh criticism and the demand for responsibility, especially from public and political organisms, was a recurring theme in the press. In particular, the responsibility of the CHS was questioned for not keeping the river beds clear of reeds, for not cleaning the channels, for not preventing the elimination of the dense mesh of tributaries, ramblas and brooks, and for not delimiting the rambla of Abanilla; the residents of Alquerías protested about the train tracks being built in the bed of the Tabala rambla; Los Alcázares threatened to take the ministry responsible to court and denounced the company that built the AP7 motorway of not adequately channelling the rambla de La Maraña, which was one of the main causes of the flooding in this municipality; elected leaders were criticised for not doing their jobs properly and asked to legislate on limitations of use, to carry out urban planning properly, to make specific plans to deal with flooding (as required by regional and national laws), or to solve once and for all the problem of health- hazardous mining waste that, after the rains, reached the southern shores of the Mar Menor, through the ramblas of Las Matildes, Beal and Carrasquilla.

21.- Compensation and payments. From the outset, the Insurance Compensation Consortium kept policy holders informed, and the councils helped process the aid. There were almost 14,000 applications for compensation (mostly for damage to homes) and, as of October 14, the Consortium had already paid 1.76 million euros in compensation. The President of the Autonomous Community said he was disappointed with the government aid of 749 million euros to be distributed among 20 provinces, which only covered 50% of the damage.

22.- Visits by politicians, personalities, and their statements. There were many articles related with visits to the affected areas by public officials and different personalities, as well as statements by political leaders in which there was no shortage of criticism and cross-accusations between the different parties. Politicians who visited the affected areas were the Spanish Prime Minister of the nation, the regional president and several advisers, leaders of other regional and national parties, the minister of defence, the Bishop of Cartagena and the King and Queen of Spain.

23.- Repairs and cleaning. The repairs and cleaning were arduous, reflecting the damage. In addition to cleaning houses, streets and roads, water had to be pumped from in houses, garages, and even fields to prevent crops from rotting. Despite the effort, several weeks after the DANA many areas remained flooded with mosquito infestations and complaints from inhabitants. In early October, the CHS repaired the Tagus-Segura Water Transfer system, and in late October the Autonomous Community began to repair damage to regional roads, beaches and promenades.

24.- Causes of flooding. The focus was of complaint was the building that had taken place in areas at risk of flooding, exposing property, people and animals to danger. Speculation, bad organisation, neglect and corruption on the part of local officials were blamed for the development that had been allowed, especially along the coast. The mayor of Los Alcázares believes that the construction of the airport, the new developments and the transformation of flood channels had contributed to the damage caused. An opinion piece mentioned the relationship between the anthropogenic sealing of the soil and the floods, stating that 40% of the municipality of the municipal area was sealed. A report by the Sustainability Observatory (OSE, 2019) indicated that tourism-driven urbanistic pressure had increased the risk. Another cause mentioned was climate change which favours the generation of DANAS and heavy rainfall, even though this was not the main cause of flooding in the case in hand.

25.- Solutions and measures. All political parties agreed that we must learn from The DANA and undertake work to prevent new floods. The inhabitants of Los Alcázares in particular (because of the floods that they have already suffered in recent years), are calling for definitive solutions. Asa result, government agencies, scientists and others have made proposals for action that the newspapers have described. Because of the criticisms that the local Government has received, one of its measures has been the creation of a Committee of Experts to seek solutions and prevent floods. The CHS has prepared a study to determine actions in the Albujón and La Maraña ramblas, including diverting the La Maraña rambla into the Albujón and channelling the Albujón rambla, the recovery of the channels of ramblas and small ramblas in the Mar Menor basin (even if expropriation is necessary) and to promote the project that will reroute the Viznaga rambla to prevent flooding in the villages near Lorca (Campillo and Torrecilla). It is also proposed to expand the floodplains and the margins of the ramblas and to construct new hydraulic infrastructures; one engineer has suggested constructing a 30 km canal in the Campo del Mar Menor parallel to the AP-7 motorway and the dual carriageway towards La Manga, completing it with several reservoirs for water collection. Environmental organisations such as ANSE, who are against new infrastructure, are committed to reducing intensive agriculture and urban projects, and suggest eliminating some of the existing structures. Geographers, for their part, call for an urgent change in urban policies and correct urban planning.

26.- Other. Although the news has been grouped into a large number of topics, some items are still difficult to classify, such as the widely repeated story that the former emergency director went to the theatre during the emergency; reports of illegal dumping into the rivers, taking advantage of the flood; references to previous floods such as that of Santa Teresa, San Miguel or San Fulgencio, prayers to the Vera Cruz (True Cross) for the victims, etc.

*Jokes***.** There was no lack of humorous passages, particularly in La Verdad. For example, the cartoon of people on a roof waiting to be rescued, the model of an oversized sardine that sits in the middle of the Segura River in the city of Murcia appearing in La Manga, the emblematic angel of the sculptor Salzillo under water or fish trying out of the water to breathe.

4. Discussion

It is worth mentioning how flooding is part of the natural dynamics of rivers, especially Mediterranean ones and are indispensable for maintaining their ecological condition. Flooding has countless benefits for society as a whole, such as the natural fertilisation of farmland, the replenishing of alluvial aquifers, the dilution of pollutants, increasing biodiversity, supplying sediments and nutrients to the deltas (Conde, 2013), or pushing back salt water. However, despite the construction of more hydraulic infrastructure works, the risk levels remain stable and may even increase, as vulnerability increases (Vallejo, 2000). In the Segura basin, where flooding is frequent (Romero Díaz, 2007), numerous reservoirs and channels have been built to regulate its network; however, the risk of flooding still remains, as seen from the effects of the DANA discussed herein, especially from the Segura river. In other places, such as the coastal municipality of Los Alcázares, the degree of exposure is high since it occupies the mouth of one rambla (La Maraña) and it is close to another (El Albujón). The space drained by both has been transformed by intensive irrigation and misplaced urban planning, so that in the face of high-intensity rainfall, the number of floods in recent years has continued to grow.

However, the DANA of September 2019 (called the Santa Maria Flood), is characterised as exceptional for the following reasons: (i) it produced one of the most devastating and catastrophic floods that to have taken place in Spain in recent years; (ii) torrential rainfall in excess of 300 mm/day was recorded in several places; (iii) it lasted five days as it moved south and then returned north, causing some areas to suffer its effects twice; (iv) the extent and violent nature of the floods, since the rivers and ramblas overflowed, flooding streets, fields and towns, and cutting off many communication routes (roads, railways and airports), and forcing schools and universities to close; (v) or the number of evacuees and the many emergency personnel deployed.

4.1. How the news developed

From the analysis of the news we have made, the logical sequence of a natural catastrophe, as identified by Quarantelli and Dynes (1977), is evident. According to these authors, the disaster cycle includes different stages, which can be summarised into: prevention, mitigation and preparation. The last of these consists of designing a series of activities that, properly implemented, will allow authorities to prepare before the impact and provide a quick response during the disaster. Once the disaster has occurred, response activities begin, including search and rescue, relief and assisting people. In the case at hand, the DANA lasted three days. Finally, there remains rehabilitation and reconstruction.

Although it is difficult to identify the beginning and end of each of these phases, in the case under study they could be specified as shown in Table 3.

Table 3. Sequence of the disaster, publication days and main topics.

Sequence of the disaster	**Date of publication**	**Main topics**
Prevention, mitigation and preparation	From the 10th to the 13th of September	1. Alert and prevention 2. Suppression of activities
Rescue, relief and assistance to people	From the 13th to the 15th of September	4. Climatological and weather aspects 5. Hydrological aspects 6. State of riverbeds, banks and beaches 7. Flooded areas and places 9. Evacuations, rescues and displacements 10. Effects on the population 12. Damage to infrastructure 13. Damage to agriculture and livestock 17. Emergency management

Response, rehabilitation and reconstruction.	After the 15th of September	3. Resumption of activities 8. Management of reservoirs 11. Damage to property 16. Solidarity with and aid to those affected 19. Declaration of a disaster area 22. Visits by politicians and personalities
	After the 17th of September	14. Damage to industry and other property 18. Damage and loss assessment 21. Compensation and payments 23. Repairs and cleaning
	From the 15th of September to the 31st of October	15. Effects on the Mar Menor lagoon 20. Responsibilities 24. Causes of flooding 25. Solutions and measures 26. Other

4.2. Differences between the two newspapers

The 435 news articles published by La Verdad and the 333 articles of La Opinión were compared to identify those that were analogous in content and the message they conveyed. Of all these, only 45 news can be classified as being the same (Table 4), with very similar contents and published on the same days, which indicates that each newspaper, with the same information obtained from different sources or reporters, treated the news with its own media centric bias (Valera Ordaz, 2016). Both newspapers focused on characterising this DANA as an exceptional weather phenomenon and proposed a climate-related emergency be declared. Priority issues in both newspapers were the rescues, evacuations and solidarity for those affected, the effects on the Mar Menor and visits by politicians and personalities.

Although the vast bulk of the news was negative and dealt with the catastrophic consequences of the floods, some positive considerations were reported such as the beneficial effects of rain in the Campo de Cartagena (which would save water for irrigation), or the increased levels of reservoirs. On the 5th of October, La Verdad mentioned the 20 $Hm^3$of water accumulated at the Santomera reservoir, and on the 27th of October that the reservoirs of the basin had increased by 18%.

We have not found any significant differences in the rigour of the news published in the newspapers analysed, although we have counted a greater number of scientific and opinion articles published in La Verdad than in La Opinión.

Table 4. Similar news published in the two newspapers.

Subject	Date	News which was the same in both newspapers
1	12 Sept.	Cleaning of ramblas
2	12 Sept.	Suspension of school classes
2	15 Sept.	Cruise ships that decide not to dock in Cartagena
2	15 Sept.	Train transport remains interrupted
2	20 Sept.	There is still no drinking water in Los Alcázares
3	15 Sept.	Classes in schools resume tomorrow
3	20 Sept.	The railway line with Albacete has been restored
3	21 Sept.	Roads are reopened, but some are still closed
3	16 Oct.	The railway line with Cartagena is restored
4	13 Sept.	Rain distribution map in the Region
4	20 Sept.	Exceptional weather phenomenon
4	24 Sept.	The Environment Ministry calls for "Climate Emergency"
5	14 Sept.	The Segura about to overflow in the city of Murcia
6	13 Sept.	Fear in Santomera and Beniel over possible flooding from the river
6	15 Sept.	Fear in the city of Murcia because of the rising water level
7	15 Sept.	River overflows in El Raal
7	16 Sept.	Floods in villages near Lorca
8	14 Sept.	The gates of Santomera reservoir opened
8	16 Sept.	Santomera reservoir manages to retain 19 Hm^3
9	13 Sept.	Rescues and flooded streets in Molina de Segura
9	13 Sept.	Many residents are evacuated from El Raal, Alquerías, Zeneta and Santa Cruz
9	17 Sept.	Numerous families in El Raal still cannot return to their homes
10	14 Sept.	Thousands of victims in the Region
12	13 Sept.	The Tagus-Segura transfer channel overflows and suffers a serious breakage
13	16 Sept.	Storm dumps hundreds of dead tuna in La Manga
15	17 Sept.	It is estimated that 15-20 days must pass for water to stop entering the Mar Menor
15	29 Sept.	Beaches in the southern parts of the Mar Menor are closed to the public because of the presence of a bacterium
15	13 Oct.	Heavy fish mortality in San Pedro del Pinatar
15	18 Oct.	Mass demonstration in Cartagena. Demand for solutions
16	16 Sept.	Wave of solidarity in Los Alcázares
16	17 Sept.	The wave of solidarity grows in Los Alcázares and other locations
16	17 Sept.	Buses are chartered to help those affected
17	14 Sept.	Defence Ministry deploys military personnel to affected areas
18	17 Sept.	Estimates of damage reach hundreds of millions
18	4 Oct.	Damage figures are given for all affected sectors
19	14 Sept.	Demands for declaration of catastrophic zone
19	20 Sept.	Mazarrón and Jumilla support catastrophic zone declaration
20	20 Sept.	Neighbours of Alquerías protest to Adif over the layout for the new high-speed train (AVE) tracks
22	14 Sept.	The Prime Minister visits the affected areas
22	17 Sept.	The Bishop of Cartagena visits the affected areas
22	24 Sept.	The Minister of Defence visits the affected areas
22	27 Sept.	The leader of the PP visits the affected areas
22	5 Oct.	The King and Queen visit the affected areas
23	8 Oct.	Mosquito plague because of stagnant waters
26	15 Sept.	The emergency general director went to the theatre in the middle of the crisis

5. Conclusions

Although it would be necessary to contrast its effectiveness, the proposed database allows information from the newspaper archives to be organised into indicators that give insight into the importance of different aspects of an episode. The sequence mentioned by Quarantelli and Dynes (1977) and the way it permits classification of the news allow the importance of each of the stages of a disaster to be evaluated independently and a comparison with other flood episodes to be made through a quantitative or qualitative contrast of each of the topics considered important. This could point to new findings, such as the importance of preparation and planning from the time one episode occurs until another appears; the perseverance and intensity of the impact and its effects on the population and the organisational systems involved and the most effective risk management strategies, etc. There are studies that involve similar approaches to gauge the importance of an event in terms of intensity of loss and magnitude of danger (Camarasa-Belmonte and López, 2016), however, there are not so many regarding the importance of such episodes as it passes through each of its phases as is proposed here.

In relation to the results of this specific case study, the tasks related with prevention and warning prior to the materialisation of the risk were relevant and consistent with what subsequently happened, to the extent of stopping school activity and, partially halting work in general for 48 hours. This was the correct procedure according to the CHS because the DANA was as one of the most devastating and catastrophic to have occurred in Spain in recent years, and the rainfall recorded could be classified as extraordinary. The rains were persistent and concentrated, causing rivers and ramblas to burst their banks, flooding streets, fields and urban centres. In the Vega Alta, from Cieza to its mouth, the Segura River overflowed in numerous places, and the area around the Mar Menor was also badly hit.

With regard to the impact of the emergency and the subsequent relief phase, the effects were multiple, the most emphasised by the press being those related with agriculture, livestock, fisheries, aquaculture, transport, tourism, marine ecosystems, on the coast, infrastructure of all kinds or personal property. Some data, measured or estimated, reveal the magnitude: 335 l/m^2 of rain fell in Molina de Segura and 264 l/m^2 in Torre Pacheco; the total volume of water in the Segura basin was 2800 hm^3 (more than twice the capacity of all the reservoirs); 51 hm^3 of water poured into the sea through the Segura river; 100,000 t of sediments entered the Mar Menor (with a content of between 500 and 1000 t of nitrates and 100 t of phosphates). Damage was estimated at 590 million euros and there were 14,000 claims for compensation.

Finally, the period of rehabilitation and reconstruction lasted a month and a half in terms of its importance in the press. However, according to the disaster cycle, the boundaries between the last event and the beginning of prevention, mitigation and preparation plans would overlap. What is interesting in the case that we have dealt with here is how important preventative actions are now regarded compared with response actions. It is also encouraging that the inhabitants concerned are calling for new planning measures or strategies to be drawn up, rather than accepting the large financial outlay in the form of public works proposed by the regional government.

From the analysis carried out, we cannot conclude that the news appearing in the press has directly motivated a response from the administration, but we certainly consider that these may have had quite an influence. One year after the DANA episode, the panel of experts, which was set up immediately after the event, has finally proposed a series of measures, in which the Community of Murcia will invest 77 million euros until 2023, with the aim of minimising the impact of the floods. These measures include actions related to the planning and improvement of the territory, the construction of rainwater collectors, flooding ponds and the implementation of the region's flood prevention plan (POTPRI).

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THE RISK IS IN THE DETAIL: HISTORICAL CARTOGRAPHY AND A HERMENEUTIC ANALYSIS OF HISTORICAL FLOODS IN THE CITY OF MURCIA

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ABSTRACT. The study of historical floods is a growing research trend that has generated numerous methodologies that aim to convert the qualitative historical documentation into quantitative information. This codification process aims to make comparable in time and space the manner in which past societies adapted to floods, and so extract the positive or negative points that can help reduce vulnerability and increase the resilience of current societies. However, the diversity of cultural and historical contexts, as well as the spatial-temporal heterogeneity of documentary sources, makes it difficult to extrapolate quantitative methods in historical climatology. This situation means that interpretative analyses of texts are still necessary as a complement to quantitative studies. In this paper, we make a hermeneutic analysis of the three most catastrophic floods that have occurred in the city of Murcia (south-eastern Spain) in the last 400 years. We complete this analysis with a historical cartographic reconstruction of a quantitative nature. Among the main conclusions, we highlight the fact that the society of Murcia had strategies to overcome catastrophes that included the whole of society and an integrated emergency management. However, the state of poverty of privation prior to a flood is a determining factor in explaining the resilience of a social system. A large increase in exposure of flood-prone areas over the past two centuries is noteworthy but unsurprising. However, it is surprising that the percentage of urban area exposed to flooding is now smaller than in the past. Therefore, if we consider hazard avoidance as a form of management, we can say that pre-industrial Murcian society was less efficient in using the mechanisms available to adapt to flooding.

El riesgo está en los detalles: cartografía histórica y análisis hermenéutico de las inundaciones históricas en la ciudad de Murcia.

RESUMEN. El estudio de inundaciones históricas es una corriente investigadora al alza que ha generado numerosas metodologías que persiguen transformar la información cualitativa contenida en la documentación histórica, en información cuantitativa. Este proceso de codificación persigue hacer comparable en el tiempo y en el espacio la forma en que las sociedades se adaptaban a las inundaciones en el pasado, con el fin de extraer los puntos positivos o negativos que pueden ayudar a reducir la vulnerabilidad y aumentar la resiliencia de las sociedades actuales. Sin embargo, la diversidad de los contextos culturales e históricos, así como la heterogeneidad espaciotemporal del material documental, dificulta la capacidad de extrapolación de los métodos cuantitativos en climatología histórica. Esta situación, repercute en que sigan siendo necesarios los análisis hermenéuticos de textos, como complemento a los estudios de carácter cuantitativo. En este trabajo realizamos un análisis hermenéutico de las tres inundaciones más catastróficas ocurridas en la ciudad de Murcia (Sureste de España) en los últimos 400 años. Completamos este análisis con una reconstrucción cartográfica histórica de carácter cuantitativo. Entre las principales conclusiones destaca el hecho de que la sociedad murciana tenía estrategias de superación de catástrofes que involucraban al conjunto de la sociedad y que preconizaban una gestión integral de las emergencias. No obstante, el estado de penuria previo a una inundación es un factor determinante para explicar la capacidad de resiliencia del sistema social. En cuanto a la forma de exponerse al peligro, es destacable el gran aumento de la exposición a zonas inundables producido en los últimos dos siglos. Esto no es algo sorprendente, pero si lo es el hecho de que en el pasado el porcentaje de superficie urbana expuesta sobre el total fuera superior, comparando con la situación actual. Por lo tanto, si consideramos la evasión del peligro, como una forma de gestión, podemos afirmar que la sociedad murciana preindustrial usaba de forma menos eficiente los mecanismos de los que disponía para adaptarse a las inundaciones.

Key words: Hermeneutic analysis, historical cartography, Huerta of Murcia, vulnerability, catastrophic floods.

Palabras clave: Análisis hermenéutico, cartografía histórica, Huerta de Murcia, vulnerabilidad, inundaciones catastróficas.

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1. Introduction

The history of society vs environment relationships is a process of frictions and imbalances in the form of traumatic impacts. These imbalances can be understood as natural risks. However, the complexity and multi-dimensionality of the factors involved in risk processes have determined approaches to their study from historicist and/or positivist perspectives. This has created conceptual problems around the definition of natural risk. The term is therefore conceived differently by researchers depending on the paradigm they represent. While some propose natural risk as a mathematical product that can be modelled and measurable in units; others argue that, as a human creation, risks have no meaning outside the perceptual and social orbit. These two tendencies are evidenced through definitions of the concept of risk.

On the quantitative side, the definitions of natural risk focus on its quantifiable nature. Villevieille (1997) writes that risk is the mathematical product of the probability of a hazardous event occurring and the estimation of damage caused by such an event. Pita and Olcina Cantos (2000) describe risk as an extreme phenomenon that produces negative impacts on the environment and society, and which are the result of multiplying the value of the hazard by the damage caused (measured in monetary units). Dauphiné (2001) defines risk as the product of the dangerousness and vulnerability that occurs in a territory.

With regard to the socio-perceptual aspect, definitions that consider the underlying human character of risk processes stand out. Calvo García-Tornel (2001) points out that the measurement of risk is always human. Beck (2002) goes further by indicating the social character of risks and argues that risk is the modern approach to forecasting the consequences of human action. In this same line, Giddens (2003) stresses that risks are creations of our growing knowledge about the world.

If we approve the postulates of the social aspect, we can confirm that risk processes show the characteristics of human behaviour that are poorly adapted to the natural environment, and so the natural component of natural risks simply plays an explanatory role in the development of a hazard event (Horacio *et al.,* 2019). The aspect which should be emphasised is vulnerability – since a non-vulnerable system is not exposed to risk and is optimally protected from danger. In contrast, a highly vulnerable system makes any activity and any natural process a risky activity. This divergence explains the fact that when faced with the same natural phenomenon, numerous damages are produced in some places and no damages in other ones. Consequently, it is essential to act to reduce vulnerability to plan a territory and protect people, especially in a scenario in which the recurrence of extreme events seems to be increasing due to global warming (Grinsted *et al.,* 2012). This is especially important for floods in the Mediterranean region (Blöschl *et al.,* 2020), where the role of people as catalysts for flooding processes has also been significant in recent decades (Barredo, 2007).

We must consider other important associated concepts of hazard, vulnerability, and exposure. Hazard refers to natural processes that can damage society (Olcina Cantos, 2008). Vulnerability is the expected differential impact in terms of intrinsic characteristics (such as political conditions, cultural patterns, educational levels, and economic development) (López-Martínez *et al.,* 2017). Finally, exposure is the amount of property susceptible to damage by a natural hazard (Pérez-Morales *et al.,* 2018). The sum of these three factors is risk, to which we can add the intensity and duration of the catastrophic event (Olcina Cantos, 2008).

The concept of vulnerability is composite and multidimensional, as well as being subject to social and political interpretations – and so the approach taken varies depending on the position of the researchers. The concept can be discussed in ecological and environmental terms (Ollero, 2020), in relation to political economics, or as a reflection of social relations and class structure. However, any analysis of vulnerability must consider the social, economic, and organisational factors that influence differing levels of vulnerability among societies (Endfield, 2007). In line with this, Calvo García-Tornel (1997) states that vulnerability is the degree of effectiveness of a given social group in adapting its organisation to those changes in the natural environment that includes risk. Brooks *et al.* (2005) argue that vulnerability is represented by a set of socio-economic, political, and environmental variables that affect the sensitivity and exposure of populations to environmental threats, and consider risk as the level of possible deterioration caused by environmental events as measured by the sensitivity or vulnerability of the exposed systems. The factors that determine the level of vulnerability in this conception depend on environmental and social characteristics, the type of risk, as well as development aspects such as poverty, health status, inequality, and political factors.

The complexity of the interactions that determine vulnerability obligates to consider concepts such as resilience and adaptive capacity. Smit and Wandel (2006) discuss the strong interconnection of the concepts of adaptation, adaptive capacity, vulnerability, resilience, exposure, and sensitivity. The term adaptation as applied to natural hazards can be defined as the ability of groups or individuals to improve and add new methods to cope with environmental conditions based on their cultural repertoire (O'Brien and Holland, 1992). Adaptation strategies are key points, as they are manifestations of resilience (understood as the ability of a system to return to the situation prior to impact with the least possible damage), and therefore represent a way to reduce vulnerability (Smit and Wandel, 2006).

It seems clear that there is great heterogeneity in the definitions around natural risk, a heterogeneity that has to do both with the complexity and multidimensionality of the problem of natural risks, and with the epistemological approach of each researcher. In this respect, it is legitimate to think that this heterogeneity will be greater if the aim is to study natural risks from a historical perspective given that the economic, cultural, and social context is changing. Furthermore, the documentary sources which enable us to study natural risks in the past are not spatially or temporally homogeneous. Therefore, a hermeneutical approach in the study of historical risks continue to be essential to achieve a correct contemporaneity of the events that occurred (Glaser and Kahle, 2020).

Despite being a recent development, historical studies are beginning to play an important role in the study of natural risk. Colten (1991) indicated that the reconstruction of a geographical progression plays an important role in current environmental litigation, partly because it enables a path to be followed in the management of crises, lessons learnt, and the evaluation of advances in knowledge of the factors generating vulnerability among human groups (and so facilitating an understanding of risk induction by societies). To show the most relevant aspects of social vulnerability, the most appropriate scale for this type of analysis is local. To improve the territorial management of risks, it is important to consider the variability of vulnerable populations to exposure to hazards (Cutter and Finch, 2007).

The power of comparison and replicability of a methodology is mainly based on its objectivity, and this is basically determined by the possibility of offering its results through numerical values (Brázdil *et al.,* 2018). For the study of natural risks in a historical perspective, historical climatology has produced numerous methodologies for the reconstruction of natural disasters for different periods and locations. For example, Prieto and Rojas (2012; 2015) develop works on how water extremes have influenced some social processes in South America in recent centuries. Glaser *et al.* (2017) have done the same for Central Europe, Brázdil *et al.* (2019) for Northern Europe, and Pfister (2011) for Western Europe. To highlight only a few regions, Nash *et al.* (2019) explore the relationship between society and natural risk in southern Africa, Barriendos and Rodrigo (2006) for the Iberian Peninsula, and Endfield (2007) for colonial Mexico. Some works have explored the possibility of establishing quantitative methodologies through contextual analysis (Gil-Guirado *et al.,* 2016, 2019; Glaser and Khale, 2020; Prieto and García Herrera, 2009; Diez-Herrero, 2020) with optimal results being obtained for regions with a common history and culture. However, all the previous works coincide in indicating that without a correct interpretation, the results remain unfocussed (Glaser *et al.,* 2010) and therefore, it is impossible to make a real comparison of past results with the present.

The main methodological problems in historical risk studies refer to the heterogeneity of documentary sources that makes it difficult to establish unified methodologies (Nash *et al.,* 2019). Cultural and religious divergences and socio-economic asymmetries also make difficult the comparison of regions and periods. However, despite the fact that the study of historical natural risks involves methodological difficulties and epistemological traps, there has been a certain unification of procedures in recent years. In particular, the brand of historical climatology has favored this unification of epistemological approaches with the common objective of learning from past natural disasters, regardless of the quantitative or interpretative approach employed. In conclusion, work on historical risks that aims to make considerations applicable today to improve the situation of people living in a territory must be based on the quantitative method, while at the same time reflecting on the hermeneutical nature of the interpretation of texts within social theory.

In this work we carry out a hermeneutic analysis of the historical information relating to the three major floods that affected the city of Murcia (southeastern Spain) in recent centuries. The *San Calixto flood* of 1651, the *Nuestra Señora de los Reyes flood* of 1733, and the *Santa Teresa flood* of 1879. In each of the centuries studied, these events were the greatest natural catastrophes caused by flood. The analysis of historical documentation shows numerous events and situations that helped or hindered the management of these disasters. From the quantitative point of view, we carried out a cartographic reconstruction thanks to the maps available from the beginning and end of the nineteenth century (Olcina y Diez, 2017). The aim of this cartographic reconstruction is to differentiate the effects of the floods in the nineteenth century from the current situation, both in absolute and relative terms. To do this, we digitised the available historical maps to establish the urban space in the nineteenth century and compare it with the urban space today. Finally, we digitised the perimeter of Murcia's medieval city wall and considered that its main role was to protect against flooding. We assigned a probable height to the wall based on archaeological work and using the height of the flood water for various return periods, and then we determined the type of flooding that the medieval wall could have withstood today.

This cartographic analysis is new and enables the first quantitative comparison between the historical and current flood zones in the study area. A hermeneutic analysis, together with quantitative methodologies, enable us to establish the spatial, social, and historical reality of the floods in Murcia. The aim is to find out directly whether the trajectories of adaptation led to greater or lesser vulnerability and resilience to flood risk over time (Messerli *et al.,* 2000).

2. Sources and methodology

Due to the intrinsic characteristics of flood risk and considering its instantaneous and perceptual magnitude, it is possible to speak of disasters or catastrophes in terms of greater or lesser affects (Olcina Cantos, 2008). The floods analysed in this work are considered disasters due to the number of deaths, the great social impact, and amount of destruction caused.

It is necessary to differentiate between two types of data sources: firstly, historical sources; and secondly, data sources of present time. Historical sources have been used for hermeneutic and historical mapping analysis, while data sources of present time have been used to analyse flood hazard and exposure as a basis for mapping analysis.

For the hermeneutic analysis of the flood of 14 October 1651 (*San Calixto Flood*); the flood of 6 September 1733 (*Nuestra Señora de los Reyes Flood*); and the flood of 14 October 1879 (*Santa Teresa Flood*), historical sources are used. The bulk of historical documentation corresponds to the Municipal Chapter Book (MCB). The MCB is an internal municipal document that textually collects all the decisions of the councillors and mayors who met regularly in municipal council meetings. This type of source is the best way to directly observe unfavourable climatic events (Perez Picazo *et al.,* 1980). In this type of document, the extractable information focuses on the consequences for the population of severe weather events and climatic anomalies (Gil-Guirado, 2017).

The second historical source are newspaper. Newspaper sources have been widely used for the reconstruction of historical floods (Rashid, 2011; Gil-Guirado *et al.,* 2016; Barriendos *et al.,* 2019). In this paper, newspaper sources are only available for the 1879 floods and the local newspapers of the time were consulted. In addition, various files, books, expert reports, and chronicles have been consulted – and these constitute the third source of historical documentation used. All the above documentation is available at the Murcia Municipal Archive (MMA) and the Murcia Provincial Historical Archive (MPHA). The analysis of historical maps has been mainly based on the maps made by the Spanish Army during the Spanish War of Independence (1808-1814). These maps offer a high level of detail for the period and are available on the online portal of the MCU (2020). In addition, historical maps were consulted in the Hispanic Digital Library online portal (Biblioteca Digital Hispánica) and other maps were found in files and reports available from the MMA.

Methodologically, the hermeneutic analysis is focused on a critical review of historical sources consulted. Following other works, a contextual analysis of the texts is the main analysis tool of this methodology (Pfister, 2011; Nash *et al.,* 2019; Glaser and Kahle, 2020).

With regard to the quantitative methodology we use data sources of present time and historical cartography in a combination of the methodologies proposed by Pérez-Morales *et al.* (2018) and Prieto and Rojas (2012) has been followed for the map analysis. Two factors need to be considered spatially for the historical and current assessment of flood exposure: the physical component (natural hazard); and the human component (Cardona *et al.,* 2012). Information on the former has been obtained from data contained in the National System of Flood Zone Mapping (SNCZI by its acronym in Spanish) of the Ministry of Ecological Transition and Demographic Challenge (MITECO, 2020). This has been developed by the ministry, following the principles in the European Directive 2007/60 on the assessment and management of flood risks for river space management, risk prevention, and territorial planning. This source provides the results of hydrological modelling in vector format for various return periods

(10, 50, 100 and 500 years). Models have been used for 10 (RP10), 50 (RP50), 100 (RP100) and 500 years (RP500). The information for the return period (RP) reports the surface occupied by water in each return period, and the height of the water in centimetres.

For the analysis of the current human component, buildings were considered in the form of cadastral plots available at the electronic headquarters of the General Directorate of Cadastre – part of the Ministry of Treasure (MH by its acronym in Spanish) – with data updated in 2019 (MH, 2020). The cadastral sources consulted were urban plots for each municipality in the study area. In relation to land occupation in the nineteenth century, the map of 1809 entitled 'Plan showing the Huerta of Murcia prepared for flooding if it is threatened by invasion of the capital by enemies' by Pablo del Villar is (available in the MECU, 2020) has been georeferenced and digitised. This map has served to indicate the study area of the historical region of the 'Huerta of Murcia'. A '*huerta*' is a Spanish word describing an irrigated area with small well-defined plots for growing a variety of vegetables and fruit trees. Huertas are a type of market garden and are often found beside waterways near towns and cities in Spain. This map shows the main urban areas of the time in the study area. Despite the great level of detail in this map, the reality of the period may not be fully shown.

The area occupied by the historical medieval wall of the city of Murcia has been georeferenced and digitised based on the 'Plan of the fortification of Murcia' by Manuel Rodríguez Hita (1812) and available in the MECU (2020). Once the old wall was mapped, the height of the wall above the current level of the city of Murcia was established on the basis of various archaeological works. The difficulty of establishing a set value has led us to model two height scenarios. Each of these scenarios has been intersected with the height of the water for various RPs (10 and 500 years) to ascertain the magnitude of the floods that the wall could have protected against. According to Montes Bernárdez (2002) the medieval wall that still stood in 1837 was between 3 and 5 metres above the current level of the city. Other archaeological works (Navarro Santa-Cruz and Robles Fernández, 2002) indicate that in some sections, the wall was 6.5 metres higher than the current height of the surrounding streets at the time of its construction. Similar figures are given by Aguilera and Megías (2014). These authors state that the height of the wall at present is 3.4 metres above the current height of the street and a primitive ground level of -3.7 metres would produce a total wall height of more than 7 metres. In this work we consider plausible a homogeneous wall height of 3.4 metres above the current height of the city (Scenario A). However, Frey Sánchez (2000) indicates that most of the walls were 4.1 metres high when they were built. If we consider that, in a conservative scenario, the city has risen 2.5 metres above this original level, the wall would be 1.6 metres above the current city level (Scenario B).

In addition, the digitalisation of the map entitled 'Sketch of the Huerta of Murcia; sections into which it is divided: surface occupied by the flood of 15 October 1879, height that the waters reached in the flood and approximate statistics of the losses suffered' by Juan Belando (available in the Hispanic Digital Library, 2020) gives us a more approximate idea of the spatial impact of this event.

Finally, and to complete the cartographic comparison, the digitisation of the previous maps together with the digitisation of a current satellite image, has allowed us to analyze the changes in the course of the River Segura in the vicinity of the city of Murcia between 1809 and the present.

The maps have been made using the free QGIS software (QGIS Development Team).

3. Study area and historical background

The city of Murcia was founded on the initiative of Abderramán II in 825 AD. It is located on the left bank of the Segura River, on a strangled meander. The city was founded to establish a habitable and stable point from which to control the area and exploit the fertile lands of the valley, while being sheltered from the greatest threat in the area, flooding. To do this, it was necessary to make a huge effort to control the irregularity of the flows of a river that often abandoned its course to create new meanders (Lillo Carpio, 2000).

The region is characterised by low rainfall (slightly less than 300 mm) with eight dry months, a summer drought, and marked inter- and intra-annual irregularity. In addition, average annual temperatures are high (over 18º C) with hot summers and mild winters. These conditions increase water stress for human populations and biotic communities, as the months with the greatest water demand correspond to those with the lowest river flows and the lowest rainfall. The months of June, July, and August (Gil-Guirado and Pérez-Morales, 2019) are especially critical in this regard. Until a few decades ago, the predominantly agricultural economy and the calendar of local crops revolved around this natural system and the variability it produced.

The current municipal district of Murcia occupies 885.5 square kilometres, and historically two distinct areas have coexisted within this large territory. Firstly, the city itself, as well as its huertas and surrounding villages; and secondly, the 'county of Murcia' with population centres far from the city and a generally distinct economic behaviour that is subject to rural traditions, and where dry farming has always surpassed irrigation.

The agricultural nature of the city and its surroundings has been – as in all ancient settlements – the key factor in the location of activities, which in this case and given the climatic conditions, has resulted in 'water determinism' above all other needs. This situation had the effect that in the city of Murcia, the defensive needs of a territory that was on the border between the ancient Christian and Muslim kingdoms were secondary. The city walls were conceived as a defence against floods, rather than military attack (Fig. 1). Consequently, in the city of Murcia, control of the surrounding space from a high defensive position has not been a priority.

The medieval wall of the city of Murcia has its origin in the period of Muslim rule and it was built between the eleventh and twelfth centuries. Although the main role of medieval walls is usually defence against enemy invasions, the case of the city of Murcia is an exception since the main role of the wall has always been as a defence against river flooding (Roselló Verger and Cano García, 1975). Already in the seventeenth century the Murcian humanist and scholar Francisco Cáscales pointed out that the wall of Murcia was built to defend against enemy attacks, and protect against floods and epidemics (Cascales, 1621). García Antón (1993) highlights the key role played by the wall in protecting the city from the flooding of the River Segura. However, it was Torres Fontes and Calvo García-Tornel (1975) who best described the defensive role of the city walls against flooding.

However, recent change in the size of the city has meant that the *huerta* has gone from being farmland for horticultural products consumed in the city, to an area of urban land reserve, and so changing the basic organisational scheme of the traditional *huerta*. This area was characterised by environmental factors that generated a historical region and a variegated landscape, homogeneous as a whole, and differentiated from surroundings by the use of irrigation. The territory presents a historical and spatial continuum that goes beyond political-administrative divisions, since, although most of the *huerta* is included within the municipality of Murcia, the historical territory of the 'Huerta of Murcia' stretches into parts of five other municipalities (Molina de Segura, Alcantarilla, Santomera and Beniel in the province of Murcia, and Orihuela in the neighbouring province of Alicante) (Fig. 2).

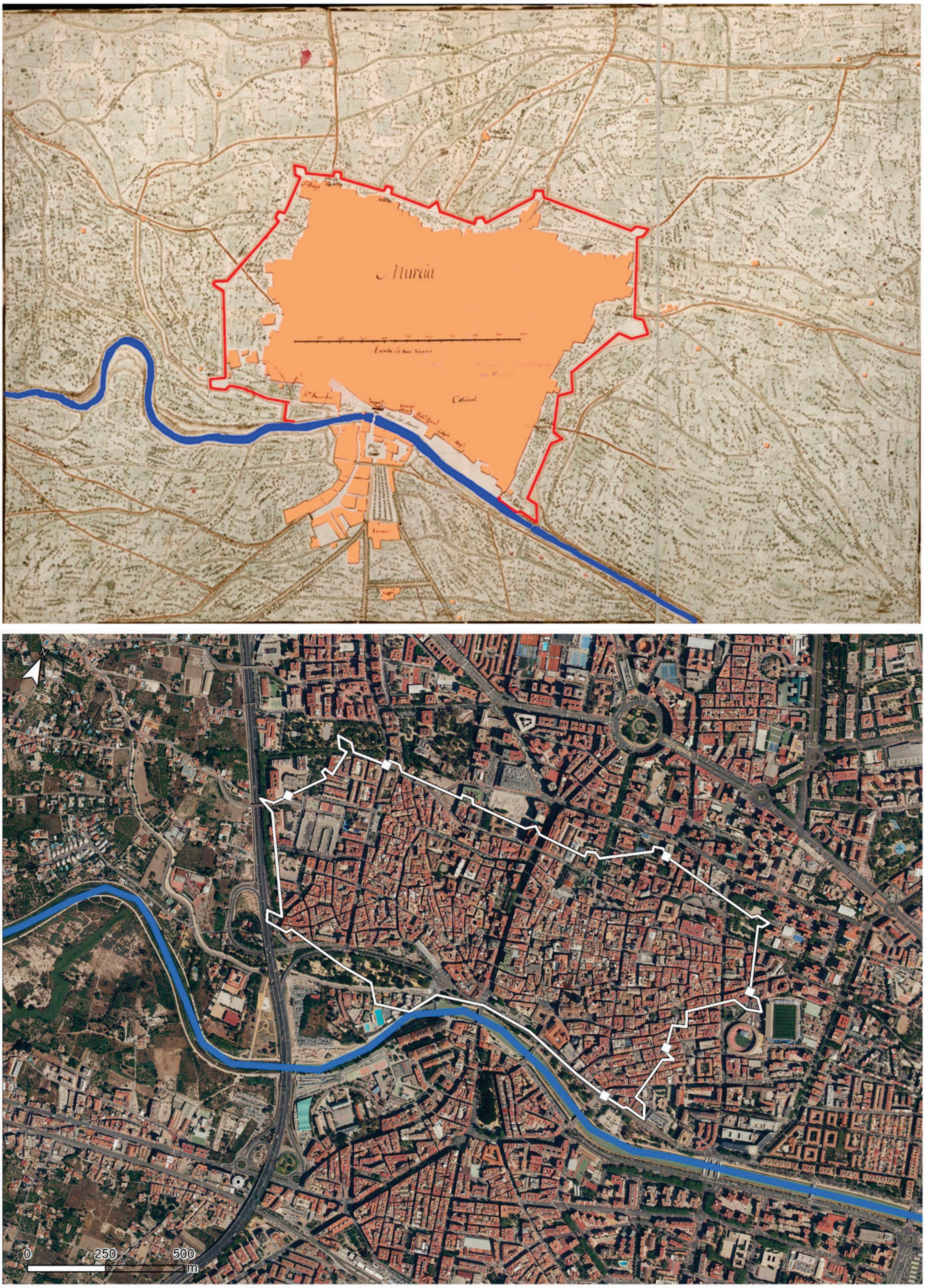

Figure 1. a) Plan of the fortification of Murcia (1812) by Manuel Rodríguez Hita; b) Current map of the city of Murcia, layout of the river and the Arab wall. Source: MCU, 2020. Note: the River Segura is coloured blue, the wall is red, and the urban area is highlighted in pink by the authors.

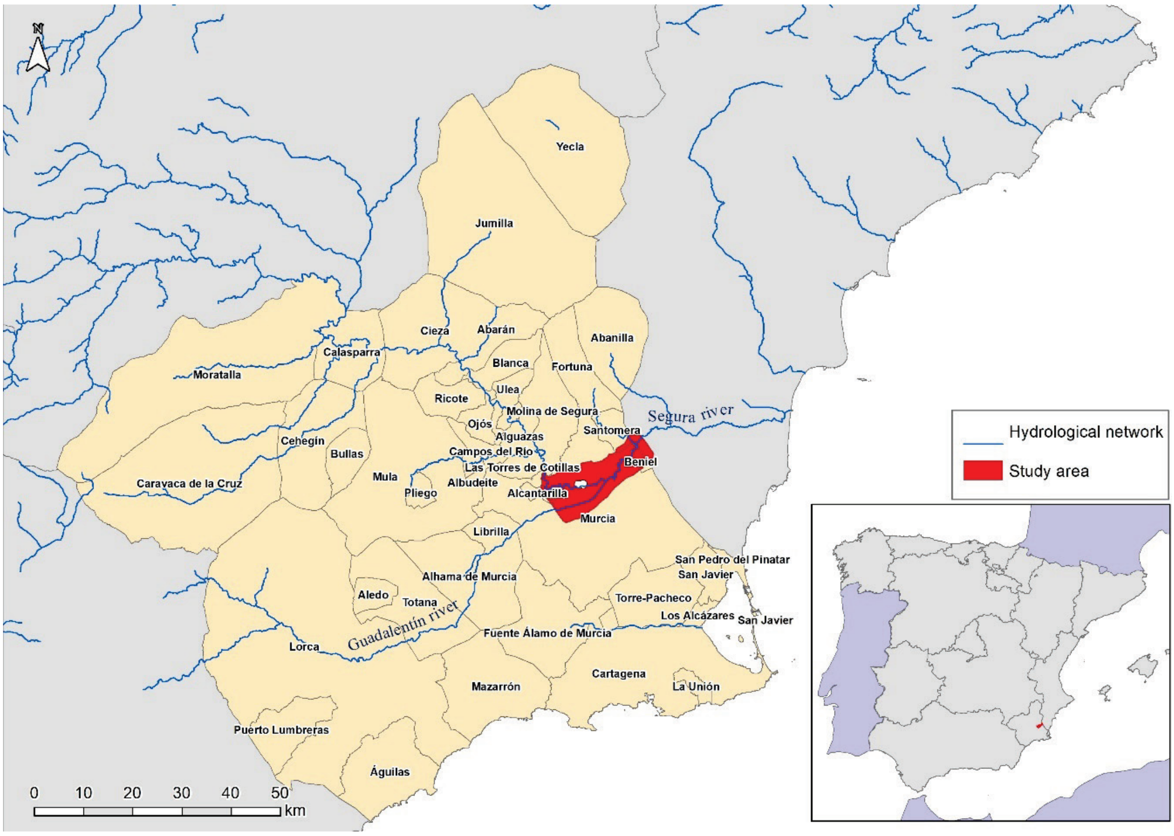

Figure 2. Study area. Notes: The perimeter of the study area corresponds to the historical region of the 'Huerta of Murcia'. The delimitation of this area has been made on the basis of an 1809 map entitled 'Plan that shows the Huerta of Murcia, prepared to be flooded if the capital is threatened with invasion by enemies' by Pablo del Villar available in the MCU (2020).

It can be seen how the River Segura, the *huerta* and the city of Murcia are intertwined in the functions of the metropolitan area, with a large part of the area being used for commercial purposes, except for some vestiges of irrigated crops (Fig. 2). This area corresponds to the Murcia Pre-coastal Depression, which is formed by of the River Segura and its confluence with the River Guadalentín. The alluvial plains – where farming is established – are made up of gentle slopes and fertile alluvial soils. The River Segura flows into the area in a NW-SE direction, with the width of its valley increasing as it approaches the city of Murcia. The Guadalentín flows naturally into the Segura, forming a large alluvial fan, a continuation of the valley floor, which runs along the Alhama fault in a SW-NE direction. However, in 1747 the Canal del Reguerón was opened to divert the River Guadalentín so that it did not join the River Segura upstream of the city. The edge of these valleys is marked by low hills.

The Huerta and the city of Murcia form the study area in this work and represent a part of the natural region identified with the valley of the River Segura after gaining width downstream from Archena and running between hills until reaching the neighbouring province of Alicante.

The natural confluence of the Guadalentín and Segura should be highlighted since the risk of flooding has determined the management guidelines of this area for centuries. This junction occurs upstream of the city in the place called 'Paso de los Carros' a few kilometres from the small town of Sangonera. The area forms a large alluvial fan (about 30 km^2) in which the topography and regime of the river increase the risk of the river leaving the riverbed (Fig. 3). This is a determining factor in the exposure and danger of this territory to flooding. Throughout the history of the city, strategies have been in place to mitigate the risk that the torrential flow of the Guadalentín imposes on these lands (Calvo García-Tornel, 1969).

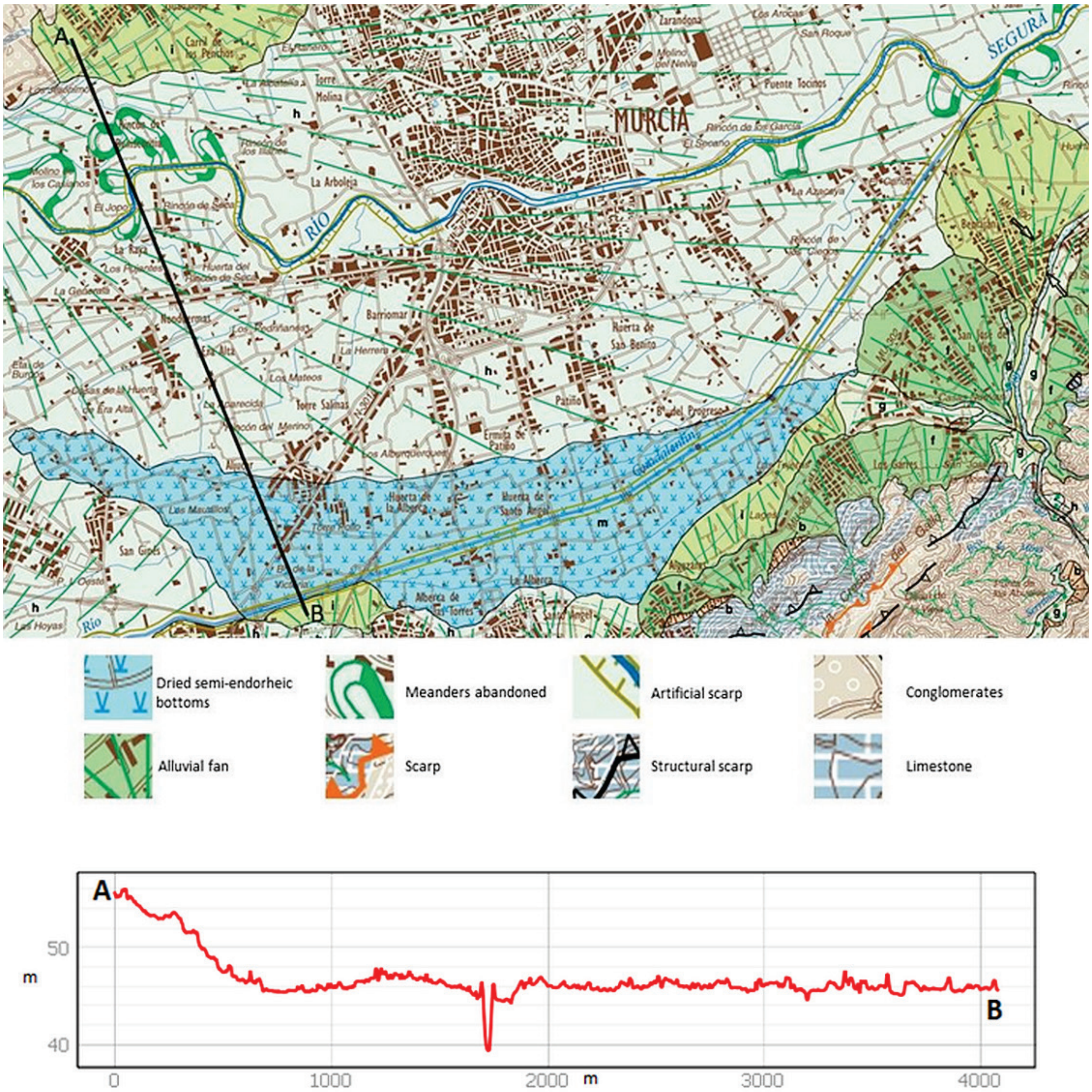

Figure 3. a) Geomorphological map of the confluence of the Segura river and the Guadalentín river in the city of Murcia and b) topographic profile. Source: Mapa Geomorfológico de España 1:50.000, IGME (2020)

This is the dual relationship that gives continuity and differentiation to the study area, given that it is characterised by the dominance and structural control of water, in order to escape from droughts and mitigate the natural lack of rainfall, while at the same time, controls are necessary to avoid sudden floods. Apart from the national and international economic and political context, these factors have determined the possibilities for regional growth, given that disasters are a burden, but the need to mitigate them is an incentive. Historical periods of development in the area, followed by population increases, were followed by periods of depression and stagnation as it was impossible to satisfy these new demands with the existing technology for farming and building structures to control water (Pérez Picazo *et al.,* 1980). The origins of this process go back to the introduction of the irrigation system in the eleventh century – which has survived, practically intact, until the end of the twentieth century (Ros Sempere and García Martín, 2012).

4. Results

4.1. The Flood of San Calixto in Murcia (14 October 1651)

The San Calixto flood of 14 October 1651 in Murcia was the most disastrous of the seventeenth century and, together with that of Santa Teresa in 1879, is one of the two floods that caused the most damage to the city.

Caused by intense autumnal rains, the sudden overflow of the River Segura caught the population unprepared (it occurred during the early hours of the morning – which was a repeated feature among catastrophic floods of the time). The damage reports tell us that the flood came from both the River Segura and the River Guadalentín, so the episode of rainfall was widespread throughout the River Segura basin (or at least in the W and NW areas). During the early hours, the city's population focused on reinforcing, with the means available, the city's defences to prevent an overflow, but a lack of resources compromised the effort.

Floodwaters ran through the city streets for three days. It was not until the fourth day that the city council was able to meet to assess the situation, which gives an idea of the size of the disaster. At an extraordinary meeting of the municipal council on 18 October, the members made a preliminary and desolate assessment of the damage. On the 19th (a Thursday), after a more thorough survey, the magnitude of the disaster was understood: buildings collapsed; livestock dead; defences swept away; a network of ditches destroyed; roads cut off; and worst of all, there were hundreds of fatalities. Such was the state of ruin that there was an exodus of survivors to higher parts of the Segura valley. The dire financial situation of the city increased vulnerability due to a lack of funds for repairs. Finally, it was agreed to accept the aid of the Crown with the subsequent exemption from taxes, the arrival of experts to assess damages, and funds allocated to help victims (Annex A. Doc. 1).

Damage to infrastructure was immediately followed by supply problems and a rise in food prices. As was normal in a disaster, neighbouring cities offered help. The first to offer was nearby Mula, despite the fact that it also suffered significant damage. One of the Crown's measures was to create a tax for all the towns of the old "Kingdom of Murcia" -territorial jurisdiction belonging to the Crown of Castilla- according to their population size to fund the reconstruction of Murcia city. The city council also required all the residents, without apparent distinction of social class, to collaborate in the repair of roads and flood defence infrastructures.

One month after the flood, the streets were remained under water and full of mud. This seriously affected commerce. In addition, buildings were continuing to collapse due to the accumulation of humidity. More than two months later the situation seemed even worse: the irrigation system continued to further deteriorate, food was scarce and expensive, the river began to occupy new spaces in the flood plain (and so mills could not grind grain), and the population continued to abandon the city for other towns. In this context, the same manager actors indirectly pointed out that the state of vulnerability prior to the event was partly responsible for the hardship caused by the disaster (Annex A. Doc. 2).

The city seems to have overcome the worst some four months after the disaster. A thanksgiving ceremony was held (Annex A. Doc. 3). However, the infrastructure remained damaged for many more months. It seemed that during this period one flood was never completely overcome, when another occurred. Thus, when another severe flood arrived in 1653, the flood damage from 1651 had not yet been repaired. This flood of 1653 was preceded by another flood of lesser size that damaged the defence systems (Annex A. Doc. 4).

Considering the means available, the systems of prevention, control, and assessment of the threat were fairly well developed in Murcia. The problem was the socio-political and economic context. It is worth noting that even four centuries ago, floods were considered a risk that required specific prevention measures. Thus, at the end of the summer, city officials began to revise the irrigation and defence system in anticipation of the autumn rainy season (Annex A. Doc. 5 and Doc. 6).

The first month after a disaster is the period when emergency work peaks, although repair work continues more than a year later. However, the first six months are when the greatest social impact is felt. Given the lack of resources, territorial problems remained considerable throughout the period and were difficult to resolve (especially the repair of the irrigation network and defence systems). From one year after the flood, adaptation measures in anticipation of future floods gain priority.

With regard to the danger, there is little information on the environmental cause of the flooding. Most of the relevant information refers to the high level of the river, and to a lesser extent, to the torrential rains and the large amount of material washed away. The seriousness of the situation forced a major effort to manage the catastrophe, help the victims, and regain stability. Most of the information refers to measures of this type. In terms of infrastructure, it was the irrigation system and, above all, the flood protection infrastructure that was most affected. Consequently, the economic disruption to farming and the problems of irrigation water supply were significant. Deaths and injuries deserve a special mention. Given the magnitude of the disaster, little importance was given to these issues in comparison with today. This was perhaps because the high mortality rates of the time, and low life expectancy, meant life was not considered as important as it is today. It is necessary to note that past perspectives and perceptions are being assessed under a current prism. At a socio-political level, it can be said that the entire social structure was affected (including urban and rural inhabitants, nobles, religious orders, merchants, and the rich and poor).

The lethal flood of San Calixto in 1651 was an important precedent for risk management in general. Constant municipal requests were made to the Crown for aid and tax exemptions (a type of declaration of disaster) and all the social agents affected were actively involved (Annex A. Doc. 7 and Doc. 8). Both high-ranking nobles and knights sent someone to work on their behalf in the recovery from the disaster. This possibility was open to all nobles, but if they did not have the money to pay somebody, then they had to work themselves. The repercussions among the ruling classes transcended the real needs of overcoming the disaster. Churchmen began an open battle against the knights and the city council. During the ceremony of thanksgiving for having overcome the flood, the priest complained that church officials did not have anybody they could send to work on their behalf – unlike nobles. In this way, the priest claimed in a populist manner that he shared the suffering of the common people (Annex A. Doc. 9). In this way, the reality that elites have appropriated legitimate popular responses to injustices, al every historical moment, and deflect the initial intention by introducing new actors according to their private interests. It is also evident that the generalisation of risk processes is not a specific consequence of modernity, as suggested by Beck (2002).

Historical documentation shows how the authorities sometimes blamed the rural population, mill owners, animal breeders, and even some town councillors, for faulty maintenance of the irrigation network and flood defence systems. Speculators were also blamed for food shortages. However, the frequent occurrence of floods in Murcia, together with the scarcity of available means, meant that people blamed nature for traditional problems that could not be avoided or prevented. Proposals made to overcome the disaster included important improvements to the destroyed irrigation and defence network as well as financial aid.

4.2. The Flood of Nuestra Señora de los Reyes (6 September 1733)

The flood of Nuestra Señora de los Reyes occurred on 6 September 1733 and was probably the most catastrophic of the eighteenth century. As in the previous century, flood defences were in a deplorable state. The inability to maintain the defences in an efficient and diligent manner, heightened the vulnerability and explained the major impact of the flood. Although the flood was much less damaging than the San Calixto Flood, it caused considerable stress for Murcia city and the *huerta*. Suffice to say that less than one month before the flood and despite the fact that the autumn rainy season was approaching, the irrigation system had been damaged, but excessive bureaucracy and a lack of funds prevented an immediate repair (Annex B. Doc. 1). Nevertheless, between 1651 and 1733 some improvements had been made to the protection systems, such as a straightening of meanders to give greater linearity to the river as it passed through the city. However, limited technical and financial resources compromised the effective application of these improvements, and above all, their conservation. The imposition of the wishes of local landowners over the public interest also played an important role in the situation prior to the flood (Annex B. Doc. 2).

On 6 September, an intense, continuous, and widespread rainfall led to a rise in the waters of the River Segura. Despite attempts to hold the banks, an overflow could not be avoided. Unlike in the case of the San Calixto flood, where the flood peaks came from both the River Segura and the River Guadalentín, the main part of this flood came mainly from the Guadalentín, and so it was less dangerous and the flows were less extreme. The immediateness of the response, the smaller scale of the flood, and because it occurred during the day, prevented a catastrophe with devastating consequences. Given the means available, the damage mitigation strategy was fairly successful in the beginning of the emergency, when rapid response groups were established to fix the damage to the defence systems and thus avoid further damage (Annex B. Doc. 3). Nevertheless, damage was considerable: mainly to crops; the irrigation and defence systems; and roads. Many homes and entire neighbourhoods were flooded. The poor quality of the buildings in the *huerta* led to many structures being washed away, and there were numerous deaths, although in much smaller numbers than a century before. Once again, the lack of a stable fund to provide for these frequent disasters made an immediate relief response difficult and left the local council without funds. There were immediate problems of food supply given the loss of crops, the destruction of crops, as well as the road closures and impossibility of milling. The result was shortages, hunger, and a major rise in the price of bread. In general, the urgent measures taken followed the same procedures as in the seventeenth century (Annex B. Doc. 4)

The notable difference between this event and that of 1651 is that while in the earlier episode it was necessary to wait four months to celebrate a church procession of thanksgiving for having saved the city from the flood, in this episode the ceremony was held just six days later. Reports said that the waters had mostly receded, and convents and some streets were already passable (Annex B. Doc. 5).

As in the seventeenth century, a damage report (which was perhaps exaggerated) was sent to the Crown. Two weeks after the flood, measures began to be taken to prevent further damage, and these focused on reducing meanders and rebuilding and improving the defence and irrigation systems. A lack of resources forced landowners to pay the costs of reconstruction. Landowners who refused or delayed were threatened with exclusion from these improvement works. Despite these efforts, 20 days later, the *huerta* and the city were still without water for irrigation and household use because of the breakdown in the infrastructure and the accumulation of sediment in the pipes.

On 30 September of that same year, another small flood made recovery more difficult. The warning systems were activated, and effective measures were established. In this case, the flood came from the River Segura and occurred gradually, due to rainfall in the upper river basin, and so there was time for the municipalities upstream of the city of Murcia to report the threat. In the end, the flow was less than expected, and the measures prevented another overflow (Annex B. Doc. 6). From November onwards, reports about this event began to decrease in the municipal records. During the following months, work continued on flood defence, irrigation, and road repairs. In March 1734, a relative recovery from the catastrophe was formally announced.

Awareness of the danger of flooding had increased in comparison to the seventeenth century, and more thought was given to preventing disasters and establishing adaptation strategies. High water levels were considered responsible for the flooding by many observers, but there was an increasing focus on the torrential rains, and above all, the materials washed away by the river, as the cause of the damage. At the same time, some observers remarked that the real problem lay in the high level of erosion of the local materials. The most significant damage was to the irrigation infrastructure. However, there was also significant damage to roads. After these damages, the effects on farming, the occasional flooding of land, and the difficulties in evacuating water were significant problems noted in the municipal records.

Murcia's dependence on official assistance and financial credit, and the lack of foresight, led to serious economic problems. The lesser intensity of the flooding led to a reduction information in relation on fatalities and injuries compared to a century earlier. The inability of local government to critically assess risks and the greater level of intervention in the territory with the better level of understanding of environmental mechanisms than a century before, led to the blame being generally placed on nature. However, there was increasing awareness of human action as being responsible for the impact of flooding. In this respect, the technicians responsible for reviewing the infrastructure were blamed for the deficiencies in the defences.

Among the measures proposed to overcome the disaster, technological improvements with respect to the seventeenth century enabled the use of new construction techniques to reduce vulnerability. However, the key measure against floods continued to be the improvement of irrigation and flood defence infrastructures.

4.3. The Flood of Santa Teresa (14 October 1879)

The Santa Teresa flood was the most catastrophic flood ever recorded in Murcia. The material damage was incalculable, and the victims were counted in hundreds. The worldwide response to the distress of the Murcian people was unprecedented (Botrel, 2019).

The flood was caused by an intense rainfall that lasted more than two days and was widespread throughout the river basin. The flood peaks that reached the city came from the River Guadalentín, as well as from the rivers flowing towards the right bank (Rivers Mula, Quipar, Argos, and Moratalla) and also from the left bank of the River Segura.

The severity of the Santa Teresa flood made it necessary to manage quickly the catastrophe. The Murcia City Council held five consecutive days of extraordinary sessions (October 15, 16, 17, 18 and 19) to deal exclusively with the management of this flooding.

On 15 October the city was completely flooded, the newspapers echoed the disaster and given the impossibility of beginning the relief efforts, they reported on the first bureaucratic responses, such as the creation of a Relief Board (a similar in effect to declaring a catastrophe). From the very beginning, it was feared that the damage to the *huerta* could be much more serious than in the city (Annex C. Doc. 1).

A news story in El Diario Información on 16 October reported: “10,000 farmers have undoubtedly lost everything they had on this sad night; and soon they will come to our streets to tearfully ask us for charity, and the authorities must help them and give bread to those who are hungry. Today the King, the Government, the whole Nation, must know that this unfortunate city has been left poor and miserable; today the voice of Murcia will be heard throughout Spain asking for help for an immense number of its children who have lost everything.”

Within the city of Murcia, the areas near the left bank of the river were the most affected. The San Benito neighbourhood (in the southern part of the city) was the first to be flooded, and as the epicentre of the catastrophe, the destruction was total. The water reached the city centre, flooding the entire San Pedro neighbourhood. The prison, the cathedral, and the neighbourhoods of San Juan and San Andrés were also flooded. The situation was worse in the *huerta*, with bodies scattered in the fields near to the city. The district of Nonduermas was completely inundated, as were the districts of Era Alta, Beniaján, Alquerías, Aljucer, Rincón de Seca, La Alboreja, San Benito, El Raal, Urdienza, and Puente Tocinos. By the 16 October, some 113 deaths were already reported despite the fact that the most affected areas were yet to be reached. In January of the following year, the official figure for victims was given as 148, although with the many missing people, the number was probably some 300 for the capital and *huerta*. In Orihuela, in the neighbouring province of Alicante, bodies from Murcia were found in the river.

The disaster attracted widespread attention in Spain and abroad, and King Alfonso XII visited the affected area on 20 October. The mobilisation of international charity was unprecedented, especially from former Spanish colonies and those that still remained (Cuba, the Philippines, and Puerto Rico). France also sent considerable aid, where the Parisian press gave considerable coverage to the event, creating a fund to help those affected and a lottery to raise funds. Help was most immediate from the other towns in the River Segura basin and the rest of Spain – and began arriving just two days after the flood.

Press sensationalism exaggerated the effects and made it difficult to obtain a clear idea of the magnitude of the damage (Annex C. Doc. 2 and Doc. 3). More than 20,000 hectares of the Huerta of Murcia were submerged, and much material was carried away by the water. In some places once the water was drained, the accumulated sediments reached almost two metres in height (Figure 4). The destruction was almost total and the damage incalculable.

Until October 22, the authorities only sought to provide relief, and from this moment onwards they began the work of rebuilding the flood defence and water distribution systems, while at the same time, they started to propose measures to avoid a repetition. These measures usually involved public works (Annex C. Doc. 4).

Newspaper reports noted a new class consciousness in the nineteenth century, differentiating between poor day labourers, landowners, and the rest. The improvement in individual and political freedoms, together with the relative freedom of the press during the reign of Alfonso XII, is evident in a greater critical capacity that pointed directly to several social practices as responsible for the destructions caused by the flood. However, following the flood, corporatism and political control of the media were also felt. On 16 October 1879 the 'Diario de Murcia' supported the ruling political powers and security forces with a front-page story that commentated: 'yesterday throughout the huerta we saw how all the councillors, the Civil Guard, firefighters, and security forces, as well as hundreds of members of the public, continued to provide relief to those in need'. The newspaper went on to suggest that the cause of the flood was divine: 'It seems that God is angry at the city of Murcia'. The political support was confirmed on the 19th: 'We repeat that in Murcia there has been no authority, nor individual with responsibilities, who has not done everything that could be done'. To this position was added an ultraconservative opinion that considered the poor – who were accused of numerous vices and bad habits – to be responsible for the social problems. A news story published on 25 October 1879 in *El Diario de Murcia* is the best example of this, and it also indirectly illustrates some of the secular problems of the population of the Segura Valley, such as a lack of a spirit of protest, conformism, and religious faith (Annex C. Doc. 5). This news story is almost an insult and serves as an example of how social tensions were increased by the flood. The same newspaper was also forced to respond to criticisms made by the more progressive and educated sections of Murcian society – who were too afraid to publicly make their observations (Annex C. Doc. 6).

From December 1879 onwards there were constant problems in the distribution of aid, and it was said all of the donated funds were being made available. Most of the funds were donations from individuals and were given to help the neediest, but it seems that a part of this aid was re-directed to help large landowners and the upper classes. Again, some sectors of the local press showed their support for local cronyism and so evidenced that social problems were an important factor of vulnerability. It also became clear that the most conservative sectors were the least inclined to spend funds on improving adaptation and resilience, and were opposed to reconstruction beyond the safest areas (Annex C. Doc. 7). Nearly three months after the flood, a realistic assessment of the number of people affected was made, and it highlighted that 9,332 people in the *huerta* had not yet been provided with clothing (while 20,000 had been given clothes). However, reports on the amount of damage were still contradictory (Annex C. Doc. 8).

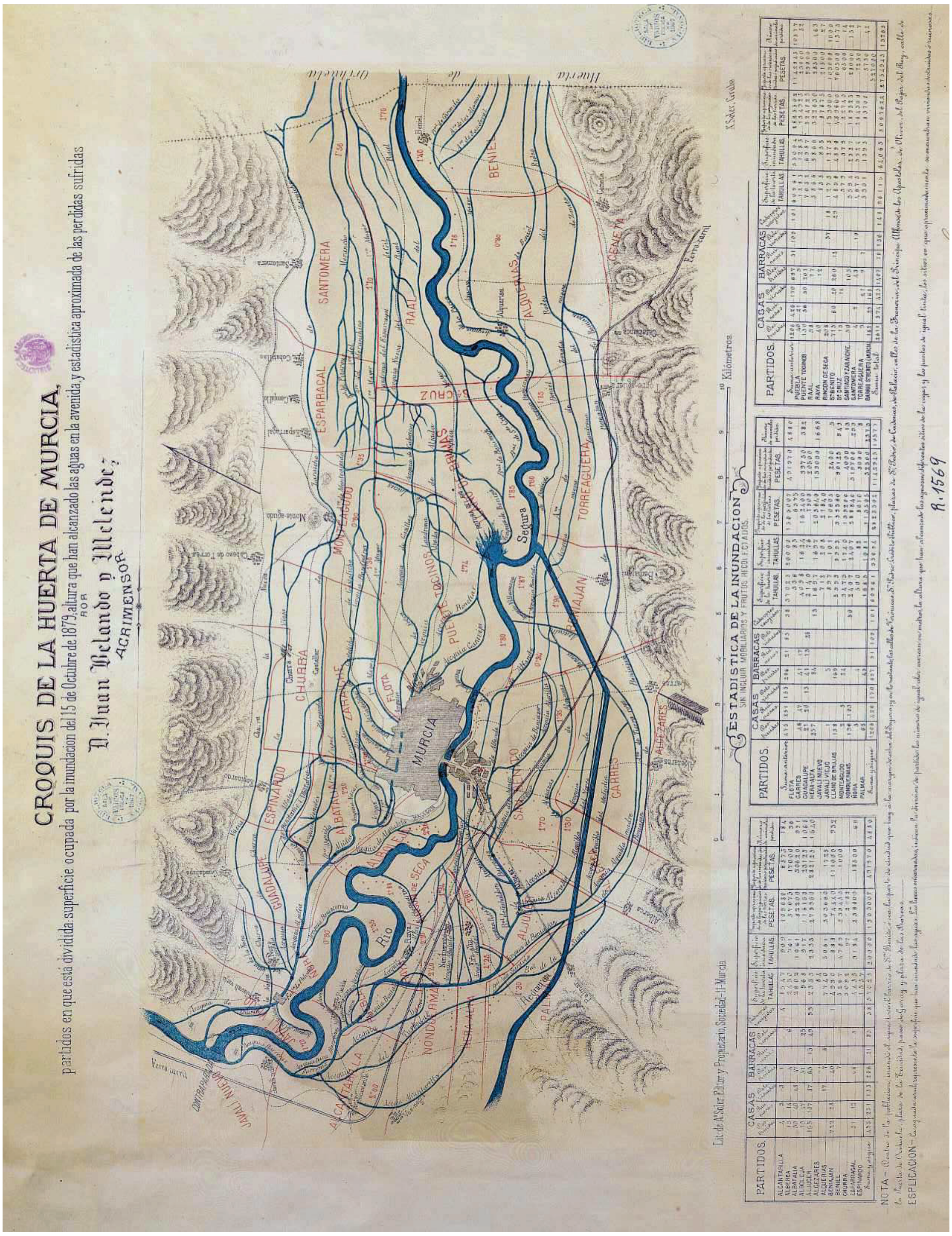

Figure 4. Sketch of the Huerta of Murcia showing the area occupied by the flood of 15 October 1879 and the height that the waters reached – and approximate statistics of the losses suffered. By Juan Belando. Source: Biblioteca Digital Hispánica (2020).

By March 1880, the flood was being overcome, or rather internalised, by the general public. Given the magnitude of the disaster, the effects continued for months and even years, while destroyed estates, houses, and roads were being rebuilt. However, by this time, normality began to return. Once again, the small farmers realised that their fate was to become poorer and more miserable than they had been just a few months before. An *El Semanario* editorial of 17 March 1880, addressed to two politicians (including General Manuel Cassola) explained this reality, as well as the continuing problems with the distribution of aid (Annex C. Doc. 9). The efforts to overcome the disaster continued at least until the end of September 1880 (almost a year later). Despite the magnitude of the disaster, less time was needed to solve the most obvious flooding problems when compared to events with comparable repercussions in previous centuries, such as the San Calixto flood.

The hermeneutic analysis shows that this flood reveals a large increase in exposure with an absence of improvements in the systems of defence, mitigation, or prevention. The population of the city had risen from 19,320 in 1755 to 29,949 in 1887. During this same period, the population of the Huerta of Murcia grew from 50,156 to 74,873 (Marset Campos *et al.,* 1981). However, a more widespread and rational use of new technology had induced a greater awareness of the natural danger of flooding. For the first time, sloping land was considered as dangerous. It should be noted that academics also pointed to deforestation as responsible for the increased impact of floods (Echegaray, 1851; Rico Sinobas, 1851; Hernández, 1885; Diaz Cassou, 1887).

Despite the enormous damage, disaster management was better than in previous centuries, mainly due to the aforementioned technical improvement and investments policy in infrastructure. As far as adaptation measures are concerned, the comparatively better budgetary situation in Murcia meant an improvement when compared to previous floods. However, problems increased in farming and livestock, as well as the flooding of land, while the impact on infrastructure was reduced. In the other hand, the estimates of deaths and injuries increased notably compared to previous floods analysed, in relation with the magnitude of the disaster.

There was greater social diversity of victims than in previous floods. However, it is evident that the impact affected more severely the least advantaged sectors, and children, the elderly, women, day laborers, and the poor appear in much of the information on those affected. Perhaps this is because the greatest damage occurred in the *huerta* – where the resident population was poor and generally engaged in farming.

At the same time, social conflict increased, although it was limited as the size of the disaster produced a certain solidarity and mutual understanding among those affected, or simply because the population was so exhausted and affected that public calls for accountability were not made. We must also consider the effects of the political manipulation of the news.

As far as the general causes are concerned, the available factual evidence meant that less blame was placed on nature and more on human actions, although not as much as was justified given the technical advances and the new nineteenth-century scientific paradigm. Again, this is explained by the manipulation of information. This can be seen from the fact that newspapers in Murcia pointed to poor farmers, and to a lesser extent the defence system and politicians, as the main culprits.

Adaptation measures experienced a major qualitative leap in the wake of this disaster. Positivist currents of the time were influenced by the fact that a large number of congresses and technical meetings were studying the danger of flooding in Murcia. The state of destruction was such that this was seen as an opportunity to reconstruct and build a better adapted system. Various administrative reforms, an improvement of construction techniques, and the rebuilding of houses in less exposed areas, were some of the new solutions considered. However, many measures were not carried out in the appropriate manner due to the conservatism of the existing powers, which meant that the most important measures continued to revolve around improving the flood defence systems.

4.4. Historic maps and defensive infrastructures against flooding in the Huerta of Murcia

The Huerta of Murcia and the city have grown in parallel with the solution to the problems caused by the River Segura. Depending on the technological possibilities, policies have developed over the centuries to rectify the course of the river. These policies were first developed between the fifteenth and nineteenth centuries (Roselló Verger and Cano García, 1975). In parallel with the expansion of the irrigation system, the growth in the settled population forced awareness of the greater risk of flooding due to increased exposure. Retaining walls were built, the most important being the Trenque del Chillerón, Trenque del Don Payo, and the most significant for the defence of the city of Murcia, the Muro del Malecón (first built in the fifteenth century and rebuilt in 1736). This latter infrastructure was three metres high, more than 1.5 kms long, and surrounded the west side of the city. Much of this wall still contains the river water as it passes through the city centre. These works corrected seven large meanders of the river between 1593 and 1692, most of which were near the city of Murcia, and there is also ample documentation available from the sixteenth century (Calvo García-Tornel, 1972) (Fig. 5).

Figure 5. Map of 1765 showing the intended cutting of a meander in the River Segura due to its effects on the Aljufia irrigation channel. Source: Murcia Municipal Archive (MMA).

Changes in the length of the River Segura in the study area are evidence of this process of straightening of the riverbed over the last two centuries. These changes have been carried out mostly in the meanders upstream of the city of Murcia and also in the stretch between Murcia and the district of Alquerías (Fig. 6). Changes in the length of the river are indicative of the new trends in fluvial policy. In 1810, the length of the River Segura as it passes through the *huerta* area of Murcia was 40,088 km, by 1879 this figure had dropped to 33,922 km, before falling to 32,704 km in 2019. A reduction of 14% and 18% respectively and in absolute terms, the River Segura has lost more than seven kilometres in length in the study area over the last two centuries.

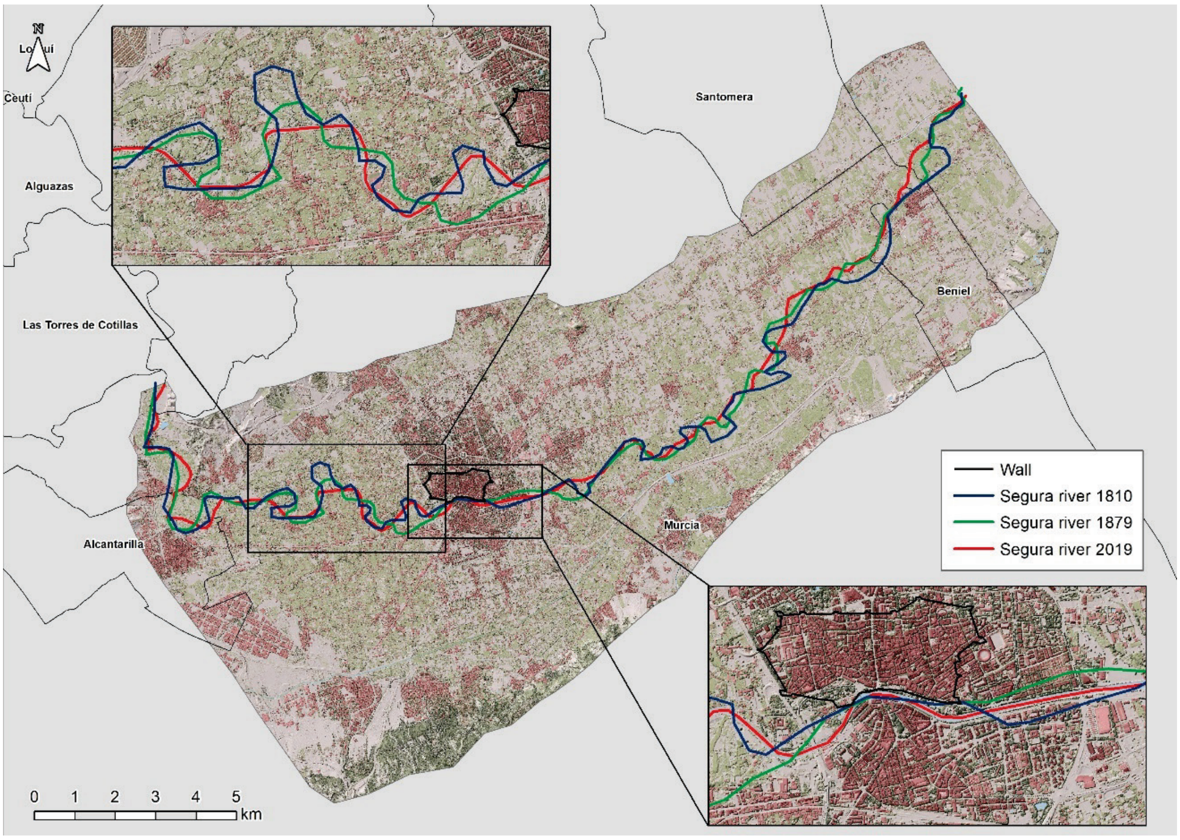

Figure 6. Changes in the River Segura as it passes through the city of Murcia over the last two centuries. Sources: the riverbed in 1810 is drawn from the map of Pablo del Villar of 1810 (MCU, 2020), the riverbed in 1879 is drawn from the map of Juan Belando 1879 (Biblioteca Digital Hispánica, 2020), the riverbed of 2019 is taken from a satellite image of the 2019 National Aerial Orthophotography Plan (PNOA) of the Ministry of Development, through the General Direction of the National Geographic Institute (IGN) (2020).

The irrigation system is also a threat to the population, due to the risk of flooding and expansion of the floodable area, but it has been planned and strictly controlled in a manner similar to a military defence system. Thus, in 1706 during the War of the Spanish Succession, Cardinal Belluga ordered the breakage of the dikes to flood the Huerta of Murcia and so prevent the city from being taken by troops loyal to the Habsburgs. Similarly, during the Spanish War of Independence, military defence plans included the controlled flooding of the *huerta*, to prevent the entry of Napoleonic troops. Figure 7 shows how entire irrigation network of the Huerta of Murcia was conceived as an integral defence system against external enemies.

The eighteenth century saw a boost to the flood defence of the Huerta of Murcia. Calvo García-Tornel (1972) remarked that thanks to an expanding economy this was the first time that solving the problem of flooding was approached in a comprehensive manner. During this period, an artificial bypass channel was completed to divert the erratic and torrential floods caused by the River Guadalentín before passing through the city of Murcia. This work became known as the Reguerón Canal and is still in service today. At the same time, at the end of this century, construction began on the Puentes and Valdeinfierno reservoirs in the upper basin of the River Guadalentín, with the aim of increasing the irrigation water reserve for the Vega de Lorca and using the reservoir capacity to slow down the flooding of the River Guadalentín – the principal threat to the city of Murcia.

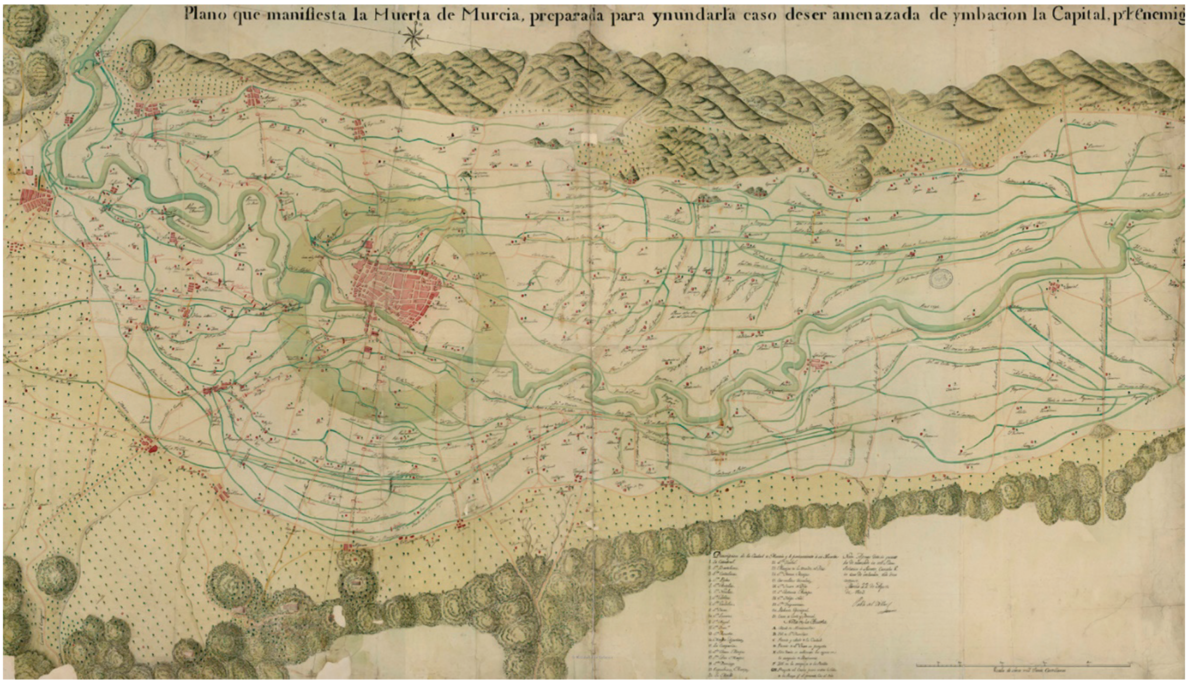

Figure 7. Irrigation system of the Huerta of Murcia, structure, and possible defensive roles: 'Plan showing the Huerta of Murcia prepared to be flooded in case it is threatened by invasion of enemies'/ Pablo del Villar'. 1809. Source: MCU, 2020.

Once again, the lack of continuity in the technical, economic, scientific, and political initiatives, reduced the effectiveness of the strategy of adaptation to the risk of flooding. According to Pérez Picazo *et al.* (1980), the economic crisis that began in the second half of the eighteenth century produced a technological blockage that prevented an improved adaptation to the environment. Nevertheless, science and technology closely followed the climatic variations of the nineteenth century, which were characterised in the study area by severe droughts and raging floods (Gil-Guirado *et al.,* 2019).

In this last aspect, the catastrophe caused by the Santa Teresa flood was highly relevant. The dimension of the tragedy, together with a new awareness of how to respond to the secular danger of the rivers Segura and Guadalentín, influenced a positive change in river management policy. The new policy focused on strengthening the banks of the river and regulating the tributaries of the Segura (especially the Guadalentín). At the same time, the Reguerón Canal was rebuilt, and a new diversion channel was built (the Paretón de Totana) with the aim of sending the waters from the Guadalentín directly to the sea (Calvo García-Tornel, 1972). The mapping of the Santa Teresa Flood (Fig. 8), showed that the area with the highest sediment and water level was in the old area of confluence of the Rivers Guadalentín and Segura (in the vicinity of the towns of Nonduermas and Era Alta). The role of the Reguerón Canal was decisive in limiting the impact of the flooding within the city of Murcia. However, the waters from the Canal del Reguerón caused great damage to the east of the city of Murcia, around the town of Beniaján. In other words, already by 1879, the flood defence system in the Huerta of Murcia was designed to lessen the risk in the city but to the detriment of the surrounding rural areas. This was corroborated in the previous section, by analysing how the damage caused by this flood was greater in the *huerta* than in city centre.

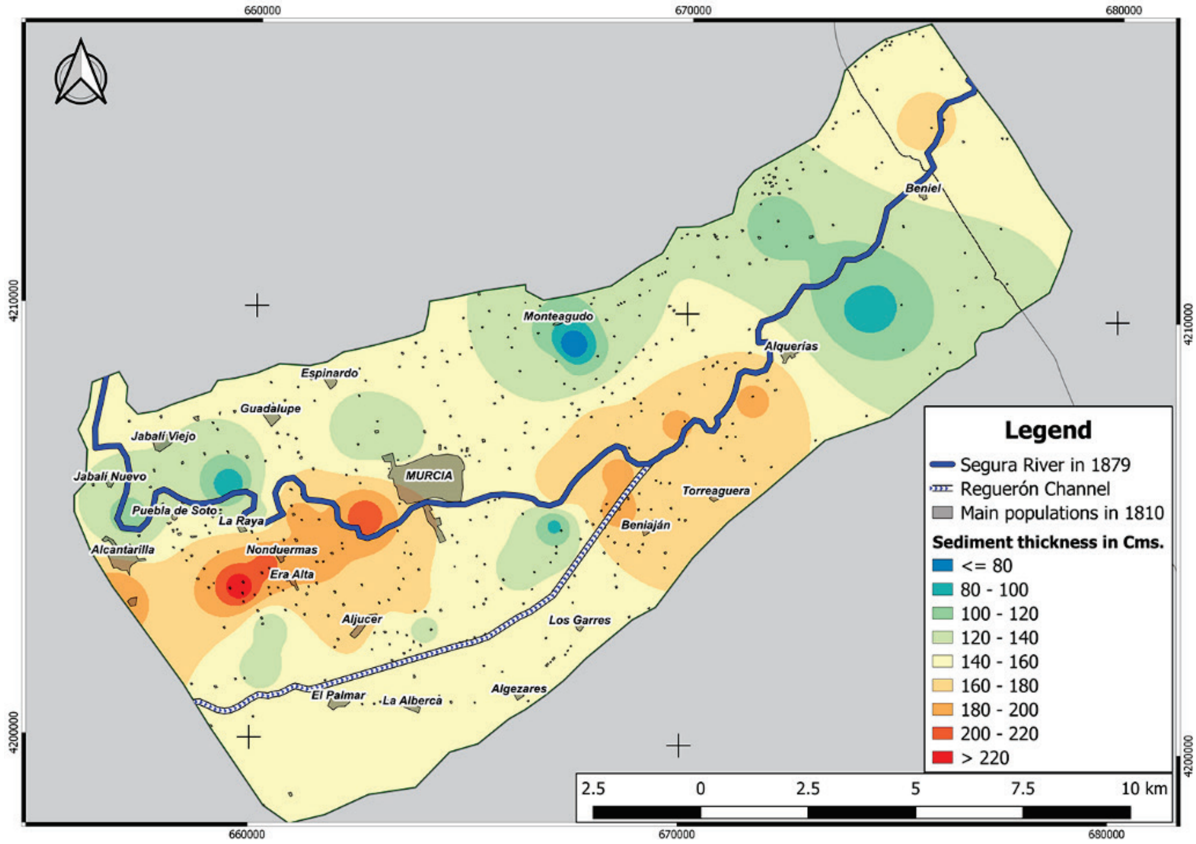

Figure 8. Sediment thickness (in centimetres) caused by the Santa Teresa Flood in the study area. Sources: the sediment heights are taken from a map of 1879 by Juan Belando (Biblioteca Digital Hispánica, 2020), while the populated areas are digitised from a map of 1810 by Pablo del Villar (MCU, 2020).

The suppression of meanders around the city of Murcia is also an example of how the flood defence system of the Huerta of Murcia was managed radially, in order to lessen the risk in the central city even at the cost of transferring the hazard to the immediate rural environment. However, perhaps the most paradigmatic example is the medieval city wall – which was conceived as a flood protection wall. In this respect, it is worth asking whether the conservation of this wall today would reduce the danger of flooding in the city centre. In the hypothetical scenario of the wall being preserved, being totally watertight, and having a minimum height of 3.4 metres above the current height of the city (Scenario A), it would represent a defence for the city centre against flooding with a return period of up to 500 years. However, if we consider these same assumptions but for a height of 1.6 metres of wall (Scenario B), then flood waters would penetrate the wall with a return period of 500 years. In both scenarios, the wall would protect against return periods of 10 years. An important point is that the most dangerous areas are located in the eastern half of the historic city (Fig. 9). If we consider Scenario A to be valid, the water would probably not have penetrated into the interior of the city, and it would have caused less damage during the Santa Teresa and San Calixto floods.

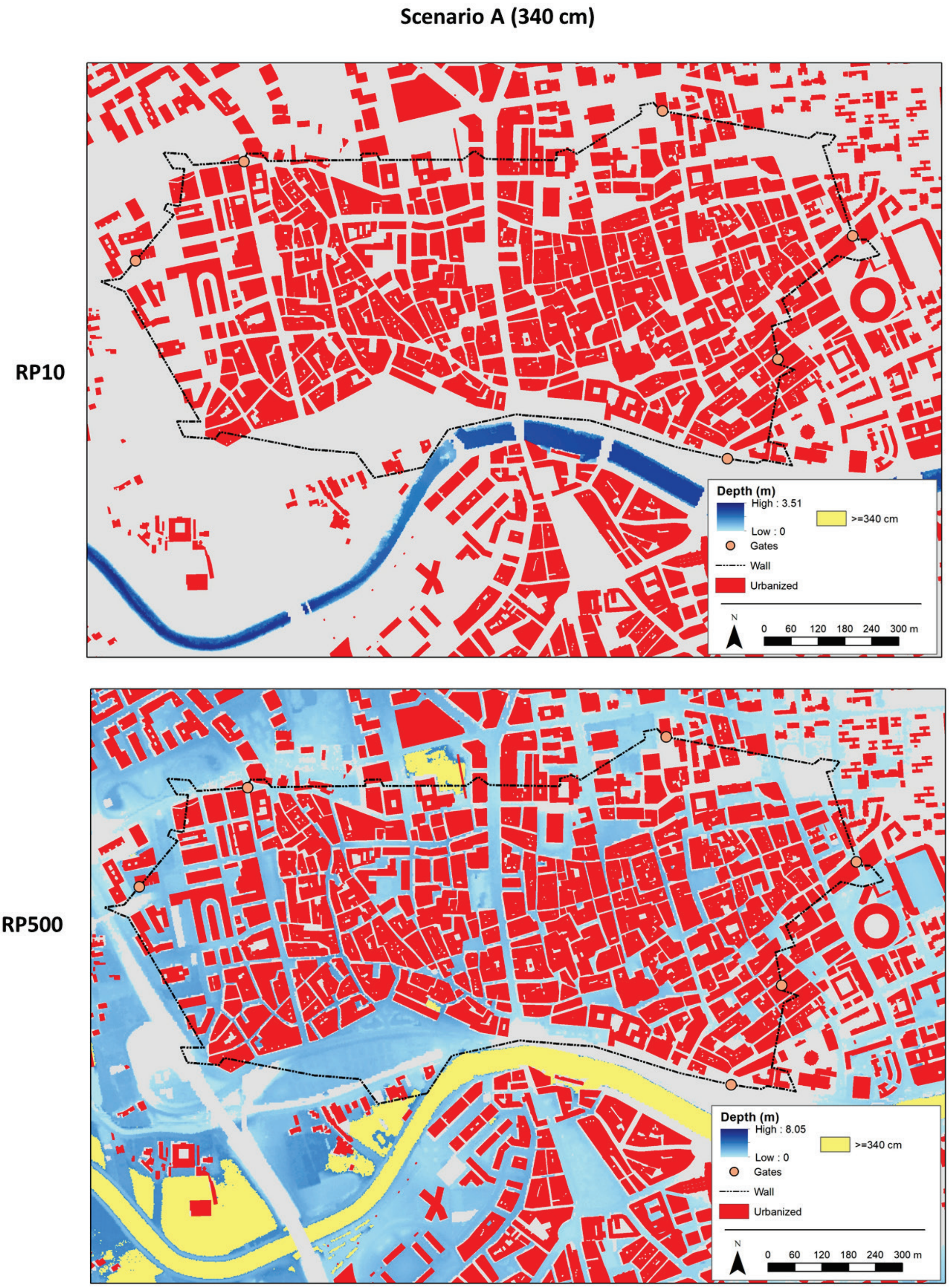

Figure 9. Modelling of the hypothetical role of the ancient medieval wall of Murcia in flood defence today. Source: the perimeter of the wall has been digitised from the 'Fortification plan for Murcia' of 1812 by Manuel Rodríguez Hita (MCU, 2020). The height of the water level has been obtained from MITECO (2020) for the short RP10 (10-year return period) and more extreme RP500 (500-year return period). The polygons in red are urban plots and were obtained from MH (2020).

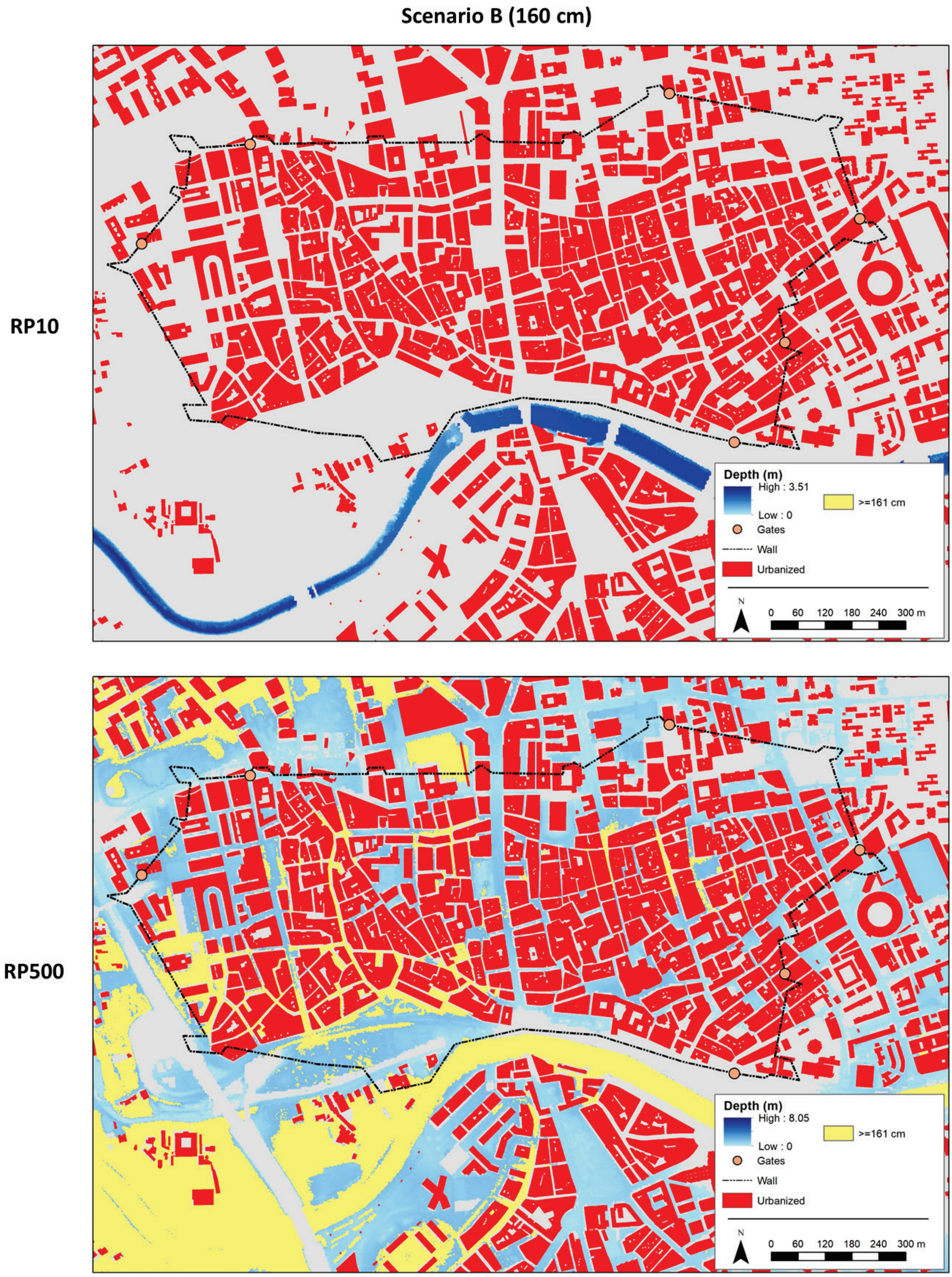

Figure 9 (cont.). Modelling of the hypothetical role of the ancient medieval wall of Murcia in flood defence today. Source: the perimeter of the wall has been digitised from the 'Fortification plan for Murcia' of 1812 by Manuel Rodríguez Hita (MCU, 2020). The height of the water level has been obtained from MITECO (2020) for the short RP10 (10-year return period) and more extreme RP500 (500-year return period). The polygons in red are urban plots and were obtained from MH (2020).

4.5. Past and present of the exposure to flooding in the Huerta of Murcia

A key issue in the analysis of historical risks is based on the question of whether historical societies, considering their technical possibilities, were more vulnerable and averse to danger than current societies. Sometimes this research question is approached from an idealisation of the ancient as superior to the present, without considering the changes in cultural, economic, and political contexts. But above all, this question is sometimes addressed without a real assessment of how exposure and vulnerability have changed over time. In the case of the Huerta of Murcia, for the first time a comparison has been made of exposure to flooding in absolute and relative terms over a lengthy period of time. It is necessary to take into account that this analysis is carried out through historical maps, and that therefore, the values referring to 1810 are susceptible to biases, data gaps, or locational errors related to the adaptation of the georeferencing to the projection system. It is also necessary to remember that hydrological modelling is used for the current scenario, so there may be significant differences with the situation in 1810. There have also been changes to topographic and hydrological factors, as well as the flood defence infrastructure. However, this analysis is the best approximation yet made in the study area.

The first point is that the study area is largely within an area that is subject to flooding. More than two-thirds of the study area is susceptible to flooding in some return period. However, there are notable differences depending on the return period considered. While the return period with the highest recurrence (10 years) is present in marginal and little urbanised areas on the southern and northern edges of the western half, the other return periods affect the study area as a whole (especially the 100-year return period and, of course, the 500-year return period). These return periods overlap with intensely urban areas. A large part of the city of Murcia is constructed in areas prone to flooding by RP100 and RP500, while other urban centres in the suburbs are exempt from the danger of flooding. The great leap that takes place between the RP10 and the other RPs is odd. In this respect, a high exposure to flooding is observed for the return periods of low recurrence (RP100 and 500), but a low exposure is observed for more frequent return periods (RP10). This is seen both currently and in the past. In other words, both in the early nineteenth century and today, the population was exposed to less frequent floods in an uncontrolled manner, but they have also been more careful about occupying frequently flooded areas. This is logical and reflects a partial knowledge of the environmental reality of the territory, as well as a perception of danger among the population and managers of the territory. However, the large increase in exposure to the danger of flooding that occurred between 1810 and 2019 is also striking (Fig. 10). This is to be expected given the socio-economic and demographic changes that have occurred over the last two centuries, and so it is interesting to analyse this pattern of change in more detail.

In absolute figures the urban area has increased from 3.8 km^2 in 1810 to 18.4 km^2 in 2019 – an increase of almost 500%. The growth in absolute values of the urban space in flood zones is worrying. Less than 1 km^2 of developed area was occupied by RP10 in 1810, but by 2019 this value had risen to 1.3 km^2 (an increase of 340%). In the case of the most recurrent return periods, the increase in exposure has been even more dramatic, with an increase of 6 and 9.3 km^2 of floodable area for RP100 and RP500, respectively. However, it is curious that there has been a decrease of 0.2 km^2 of floodable space for RP50. In other words, there has been an absolute decrease in the occupation of this type of floodable area, which must be due to the implementation of adaptation measures to reduce exposure. These figures suggest that despite an absolute increase in exposure to flooding, there has been an improvement in the adaptation model, derived from a reduction in vulnerability, which has led to a relative decrease in floodable space (Fig. 11).

While in 1810, 10% of the urban area was occupied by the RP10 floodplain, in 2019 this figure had dropped to 7%. However, the most important differences are found in the other return periods. While in 1810 almost 60% of the developed area was flooded by RP50, in 2019 this figure was 11%. Even for the less recurrent return periods, these differences remain, since in 1810 some 88% of the developed area was within the RP500 floodable area, while in 2019 this figure, although also high, had fallen to 66%. Therefore, while the absolute values show a large increase in exposure, the relative values show an improvement in the pattern of land occupation. This change in land use can also be seen in that in 1810 there was only more safe urban area than floodable area when intersecting for RP10, but by 2019 this pattern was also produced for RP50 and RP100.

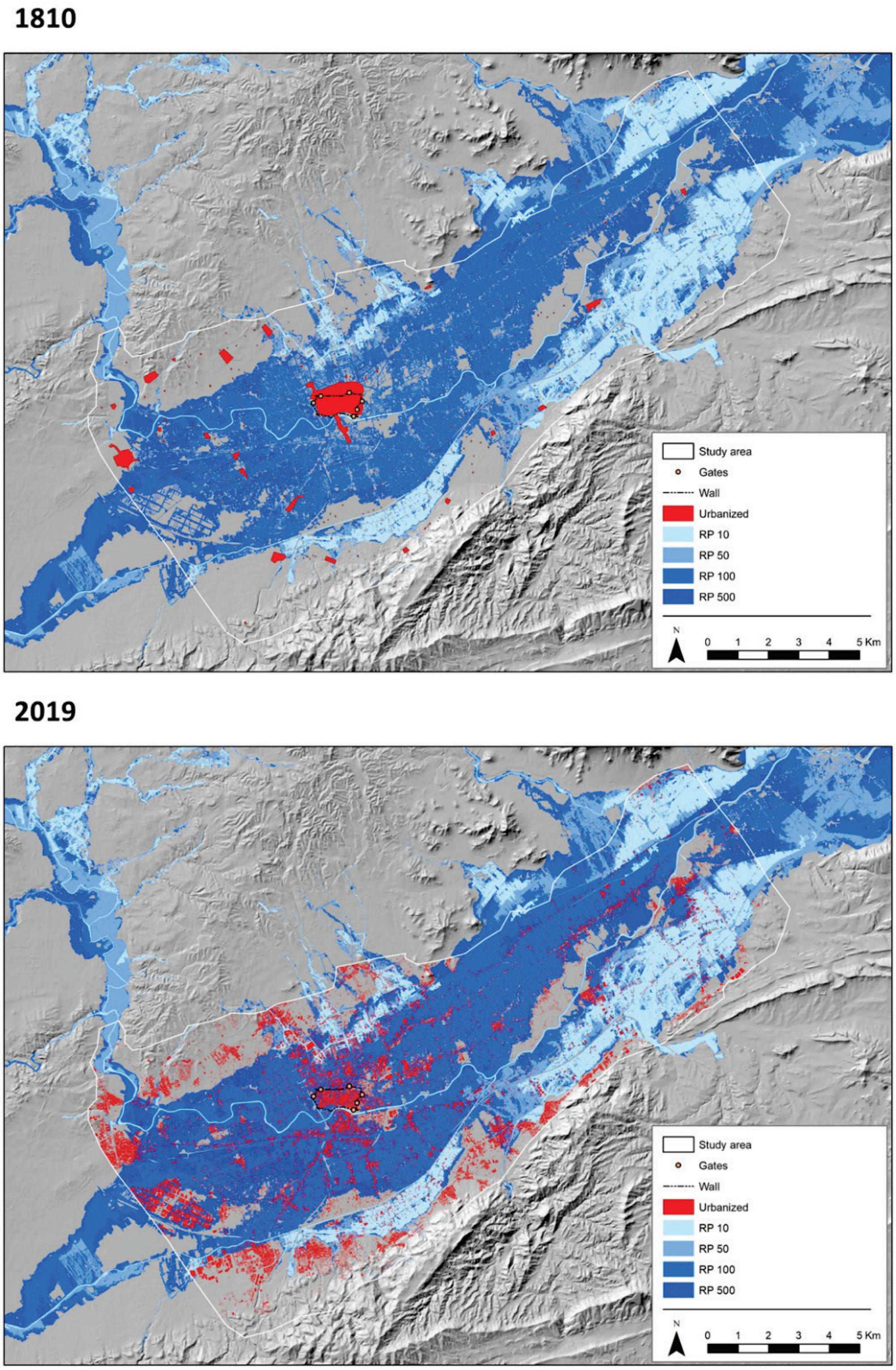

Figure 10. Evolution of flood risk over the last two centuries in the Huerta of Murcia. Source: The various return periods (RPs) have been obtained from MITECO (2020). The polygons are urban plots and have been obtained from Pablo del Villar's map of 1810 (MCU, 2020) for 1810 and from MH (2020) for 2019.

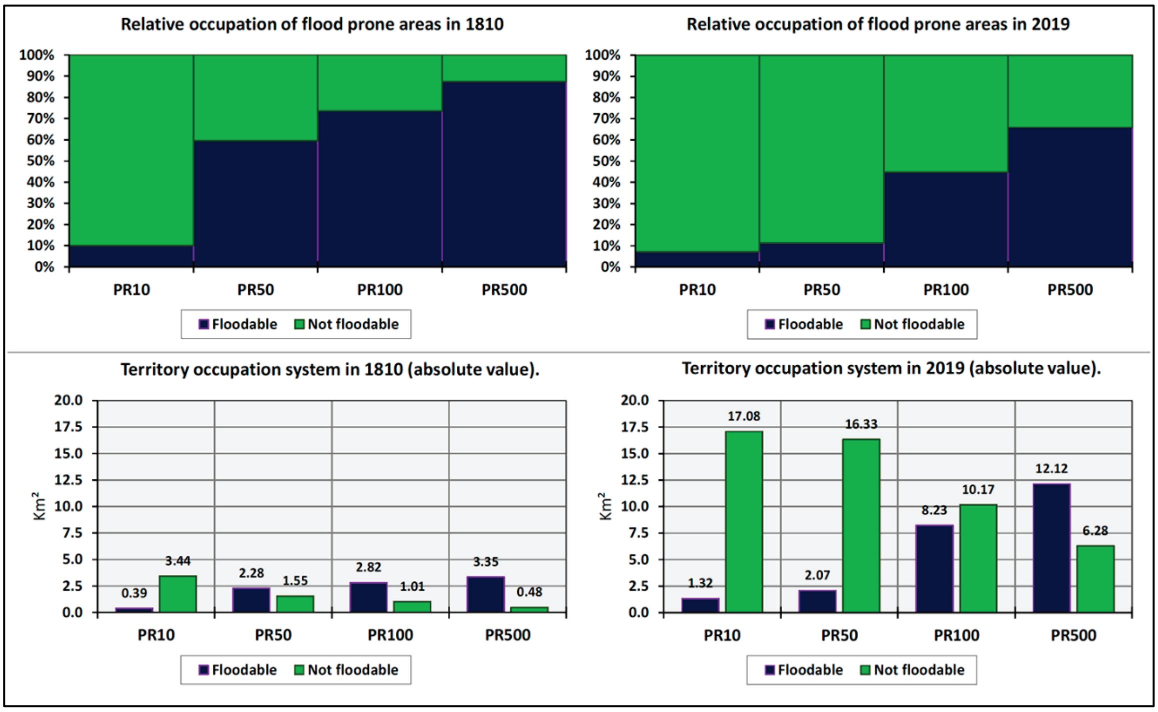

Figure 11. Evolution of flood risk over the last two centuries in the Huerta of Murcia. Source: The different return periods (RPs) have been obtained from MITECO (2020). The polygons in red are urban plots and have been obtained from Pablo del Villar's map of 1810 (MCU, 2020) for 1810 and from MH (2020) for 2019.

5. Discussion and conclusions

Hermeneutic analysis shows that, at least in the study area, the generalisation of a risk process is not a specific consequence of modernity, as indicated by Beck (2002). Giddens (2003) pointed out that the essential role of a welfare state is to mitigate risk for its inhabitants. However, the working classes were governed to further the interests of the oligarchy, and various subsectors of the oligarchy tried to win popular support and thus exercise power over the other governing classes, under the threat of using this power against them, but never to the extent of putting the system itself at risk.

Research on the analysis of vulnerability and risk in differing spaces and periods shows the difficulty of studies involving complex adaptive socio-ecological systems (Holland, 1995; Adger, 2006). Partiality the positioning of private interests over and above the resolution of general problems is the variable that makes it difficult to fully understand this process. Since society as a whole can behave in an adaptive manner in the face of situations of stress or change, but when solutions depend on a few individuals, we move out of the optimal eco-social terrain, and enter unpredictable personal and psychological terrain. Considering that society as a whole can behave adaptively in stress or change situations, if the solutions depend on few people this moves away from the ecosocial optimum terrain to enter in the unpredictable personal and psychological terrain.

It has been demonstrated that hermeneutic analysis is important to transcend the mere description of events that occur during a disaster and to highlight the problems and potentialities of each period in a historical key. Historical analysis of text shows the idiosyncrasies, potentialities, and weaknesses of each historical moment. These should be considered when planning new projects or scenarios of water use, since doing so enables the identification of inertias with respect to the most affected sectors, and this facilitates an extrapolation of the analysis to the present time to optimise planning.

The intensity of the event, the conditions of the population, the hydrological dynamics, and socio-political and economic conditions in the face of the risk of flooding explain the differences between centuries. The suddenness of floods means that immediate management is largely improvised, although improvements in this respect can be seen over the centuries. Changes begin to take place from the eighteenth century onwards thanks to improvements in infrastructure. Nevertheless, slowness in the implementation of solutions to problems leave the system in a precarious situation, so that, the effects of a flood are never surpassed definitively before another flood strikes. Throughout the entire period studied, the cause of the flooding was understood in a more or less scientific way. However, when it came to dealing with the difficulties, the appropriate measures were not taken because the managers of the territory were faced with a bureaucracy and level of poverty that slowed any actions. Throughout the study period, the most vulnerable people were often left out of decision-making because of their limited participation in power structures and poor access to resources. Public policies for intervention to reduce vulnerability must recognise the environmental characteristics and identify the inequalities and social implications of risk to create a framework for greater resilience.

Historical cartographic analysis has enabled a better understanding of internal flooding processes, as well as a better characterisation and contextualisation of the complexity of the study area. Thanks to the use of old maps, we have delimited a historical region such as the Huerta of Murcia. Due to its complexity and internal structures, that geographical space escapes a simple administrative delimitation. The use of old maps enables us to understand the spatial patterns of flooding for the Santa Teresa Flood and to relate these patterns to the local flood defence system. The entire protection system has been generated in a secular way to protect the city of Murcia from danger, at the cost of increasing the danger in nearby rural areas. The Reguerón Canal and the strategy of shortening the meanders in the River Segura are a good example in this respect. When asked if the flood adaptation strategy was more appropriate in the past than it is today, we can say that it was not. On the contrary, the population was more vulnerable to floods and was exposed to them in a less adapted way. Although it is true that there were complex systems of protection against floods – such as the medieval city wall. But this wall ceased to be useful centuries ago. After the Christian conquest of the Kingdom of Granada at the end of the fifteenth century, Murcia ceased to be a frontier territory and the wall gradually lost its defensive role. In fact, it was a brake on urban development, to the point that a municipal grain warehouse, built in 1629, was erected on part of the wall (Roselló Verger and Cano García, 1975). Therefore, the wall has not served against flooding for at least the last 400 years.

It is interesting to observe how the two most catastrophic floods in the city of Murcia (San Calixto and Santa Teresa) occurred when the wall was no longer functional. Perhaps its conservation would have substantially reduced the level of damage. If the wall were conserved today, it would protect the historic centre of the city of Murcia from the most severe floods. Finally, the most important fact that we have been able to highlight is that, despite the enormous absolute increase in exposure over the last two centuries, the type of exposure has improved substantially in relative terms. Even today there is less surface area exposed to RP50 than in 1810. This improvement in the system of adaptation is probably due to the implementation of legal controls of land use that limit exposure to flooding (Pérez-Morales *et al*., 2018). These changes have contributed to a reduction in institutional and political vulnerability (López-Martínez *et al.,* 2017). With regard to the possible explanation as to why people were protected in a less efficient manner even though they were aware of the continuous danger of flooding, a hermeneutic analysis has enabled a better understanding of the contradictions faced by a pre-industrial agrarian economy such as that of the Huerta of Murcia (Pérez Picazo *et al.,* 1980).

A system based on irrigation needs to occupy a space where water can be easily transported despite the constant danger of flooding (Calvo García-Tornel, 1972). This unprecedented cartographic analysis, together with the analysis of historical texts, has made it possible to establish what we could call "the *huertan farmer* paradox". That is, a model of occupation of the territory that revolves around the following contradiction: greater exposure to the danger of flooding in order to prosper economically, which implies a high probability of suffering more floods that cause serious losses in the economy of the area. With great stoicism, the people in the Murcia countryside adapted to the fact that their lives could suddenly become impoverished and miserable. The lack of social demands made after the great floods (Pérez Picazo *et al.,* 1980) may be explained by the fact that the people was aware of the danger, and so they only demanded short-term management strategies. Such a system is full of contradictions but remains, nevertheless, socially resilient and can be understood as the ability of society to internalise adversity and adapt to new realities.

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Annex A

Main text in historical documents on the flood of San Calixto in 1651

Doc. 1: Murcia on Thursday, October 19, 1651 (*MCB of 1651. MMA*): "*Que por cuanto por la inundación de la avenida grande del río de Segura el sábado 14 por la mañana que fue con tanta furia que cogiendo a esta ciudad descuidados sin ser posible prevenir el remedio como con tanta furia que ha roto el azud luego por otra parte dejando su término ordinario y toda la huerta arramblada, llevándose los frutos sembrados, ganados mayores y menores, derribando torres, barracas, casas y barrios enteros y los conventos de religiosos de San Agustín y Religiosas Capuchinos [...] y después de esto se ha roto el malecón y caído la pared del río desde la puerta del Convento de San Francisco que son las principales defensas que esta ciudad tenía para las avenidas del Río y cada día con la mucha agua que entró en las casas y abrió los cimientos, se van cayendo y han muerto muchas personas por cuya causa la mayor parte de los pocos vecinos que había se salen y se van a diferentes partes por conservar sus vidas. Los reparos de estos edificios y roturas requieren pronto remedio por ser para la conservación de esta ciudad y por hallarse sin fuerzas ni caudal para poderlos hacer ni efectivo de sus propios de que valerse por estar extenuados y con muchos embargos por diferentes acreedores que hay a ellos por diferentes créditos [...]. Por lo tanto, acuerda la ciudad se dé cuenta a su majestad del miserable estado en que se halla esta ciudad con el dicho suceso, suplicándole sea servido de enviar persona que vea los dichos daños y trate de su remedio socorriendo a esta ciudad para las dichas necesidades con la cantidad que fuera servido, como lo espera de su grandeza*".

Doc. 2: Murcia on December 26, 1651 (*MCB of 1651. MMA*): "*en el estado en que se halla esta ciudad con los daños que ha recibido con la peste que se padeció el años de 1648, con que murieron más de 60.000 personas y la plaga de langosta, falta de frutos, quema general de la hoja para la cría de la seda y con la inundación del río de Segura que sucedió en 14 de octubre que fue tan grande [...] y por haber roto el río el azud de donde toman las acequias agua para regar la huerta y por diferentes partes habiendo dejado su curso ordinario y los vecinos que había viendo el riesgo en que tienen expuestas sus vidas que con media crecida del río por haberse roto el paredón de argamasa en que se batían las aguas desde la puente hasta el convento de San Francisco se han ido y ausentado a otras poblaciones de suerte que su vecindad no es hoy de 50 vecinos y cada día se va minorando con la falta de trigo y necesidad que se padece de todo lo cual esta ciudad tiene puesto en consideración a su majestad suplicándole sea servido de mandar se haga una rebaja considerable en el precio de cabezón de Alcabalas*".

Doc. 3: Murcia on February 10, 1652 (*MCB of 1652. MMA*): "*que se baje el santísimo Sacramento de la Torre donde esta desde la inundación del río [...] y misa solemne de gracias a su divina majestad por habernos librado del riesgo tan grande de la inundación*".

Doc. 4: Murcia on June 21, 1653 (*MCB of 1653. MMA*): "*que por cuanto el río de Segura viene creciendo y por la poca firmeza que tiene la presa estacada del azud respecto de no haberse podido acabar*".

Doc. 5: Murcia on November 8, 1650 (*MCB of 1650. MMA*): "*el sobreacequiero en que da cuenta de algunos daños que necesitan arreglar en el río y partido de esta ciudad [...] para la seguridad del río cuando puede tener riesgo esta ciudad*"

Doc. 6: Murcia on September 5, 1651 (*MCB of 1651. MMA*): "*se limpia el val de lluvia para prevenir la época de lluvias y avenidas del río*".

Doc. 7: Murcia on October 19, 1651 (*MCB of 1651. MMA*): "*la mayor parte de los pocos vecinos que había se salen y se van a diferentes partes por conservar sus vidas y los reparos destos edificios y roturas requieren pronto remedio por ser para la conservación de esta ciudad y por hallarse sin fuerzas ni caudal para poderlos hacer ni efectivo de sus propios de que valerse por estar extenuados y con muchos embargos por diferentes acreedores [...] acuerda la ciudad se dé cuenta a su magestad del miserable estado en que se halla esta ciudad con el dicho suceso suplicandole sea servido de enviar persona que vea los dichos daños y trate de su remedio socorriendo a esta ciudad para las dichas necesidades con la cantidad que fuera servido, como lo espera de su grandeza*".

Doc. 8: Murcia on November 11, 1651 (*MCB of 1651. MMA*): "*los capitanes de las parroquias han alistado la gente de sus compañías para que vayan los días que les tocare al dicho reparo o por sus criados a jornal por su cuenta y porque por ser beneficio común y obra pública toca que generalmente a todas sin ninguna excepción pues no hay privilegio para librarse de los riesgos y daños de la inundación que en esta ocasión la han padecido los santuarios y las religiosas más recogidas y porque se ha entendido que en algunas personas a causado escrúpulo el trabajar, por si o contribuyendo para el dicho reparo por decir que tocaba a los buenos hombres llanos y no a los caballeros hijosdalgo y porque esto se ejecutaba así cuando el dique estaba entero y sin ninguna brecha solo para reforzarlo y subirlo y ahora milita diferente razón pues roto por tantas partes con la menor crecida se inundará y destruirá esta ciudad y para este reparo no puede haber accidente que lo embarace [...] y en consideración de destas razones y por la imposibilidad en que esta la ciudad el señor obispo de Cartagena y los señores dean y cabildo y todo el estado eclesiástico debe ayudar a obra tan justa y en que tienen tanta parte y parece que lo harán con gusto pues no se puede esperar menos de sus muchas obligaciones y de sus piadosas atenciones*".

Doc. 9: Murcia on February 12, 1652 (*MCB of 1652. MMA*): "*se había de hacer en procesión y misa con sermón en hacimiento de gracias de habernos librado de tan gran peligro, que el cabildo convidaba a la ciudad por si tenía a gusto de asistir y la ciudad con toda estimación aceptó [...] Don Diego Riquelme canónigo de la dicha Santa Iglesia y en el sermón dijo que los castigos que dios Nuestro Señor enviaba a esta ciudad era por el poco respeto que se tenía a los sacerdotes, la poca atención con el señor obispo, que contra su voluntad y en su ofensa había visitado sus graneros habiendo asistido por sus sacerdotes en la inundación con el agua a los pechos repartiendo limosna de pan generalmente cuando los gobernadores y particulares estaban retirados en sus comodidades sin padecer ninguno; que la ciudad no cumplía sus votos y que los que eran de parecer que no asistiesen en la dicha Santa Iglesia eran demonios y otras cosas en ofensa de la ciudad hablándole cara a cara [...] habló ocasionando alborotos en desorden de su ilustre autoridad, causando con sus predicaciones escándalo notable y murmuración siendo cierto que la ciudad y los caballeros que la componen con la mayor atención como se debe creer de sus empleos y obligaciones han hecho y hacen la estimación que se debe [...] y que la visita que se hizo de los graneros del Señor Obispo no fue por acuerdo de la ciudad ni tubo ninguna inteligencia y cuando los caballeros capitulares que asistían lo entendieron que fue con publicidad y por dar satisfacción al pueblo que padecía necesidad con la falta grande que había de trigo hasta conocer el que el Señor Obispo tenía con la mayor cortesía que se pudo y sin ninguna inquietud, fuerza ni escándalo como consta por papeles [...] y que muchos caballeros regidores arriesgando sus vidas solicitaron el remedio de las necesidades públicas en la inundación incesantemente y las socorrieron dando para ello el trigo que tenían para el sustento de sus familia y haciendo las limosnas que podían y el señor obispo y el cabildo eclesiástico habiendo sucedido la inundación el sábado 14 de octubre no empezaron a hacer limosna de pan hasta el miércoles siguiente*".

Annex B

Main text in historical documents on the flood of Nuestra Señora de los Reyes in 1733

Doc. 1: Murcia on August 11, 1733 (*MCB of 1733. MMA)*: "*que la Contraparada del Río Segura que refrena las aguas para el riego de esta huerta, necesita de algunos reparos prontos para su conservación*".

Doc. 2: Murcia on February 6, 1733 (*MCB of 1733. MMA)*: "*obras para dar salida a las aguas del Río Sangonera arregladas al mapa y Proyecto de Don Pedro Thomas a la que se han opuesto en el Real Consejo los Señores Conde del Valle San Juan; el de Montealegre y otros interesados en esta huerta"*.

Doc. 3: Murcia on September 6, 1733 (*MCB of 1733. MMA)*: "*riesgo en que se halló la población con la avenida del río: la ciudad teniendo presente que la crecida ha sido tan inopinada y soberbia que se mantiene creciendo hallándose tan elevada que a derramado en lo general de la huerta y sin servirle este desahogo continua tomando agua y amenazando total ruina a esta población, mayormente por los sitios del malecón, puerta de San Francisco de del Puente de Madera, la que nombran de Orihuela y otros, por la debilidad y flaqueza de sus terrenos y empezado a derramar por algunos de ellos con general clamor lo que ha precisado al Señor Corregidor y distintos Caballeros Capitulares con botar varias tropas de vecinos y ocurrir a precaver dichos sitios reforzándolos con fajinas, tablachos y estacadas a fin de evitar el riesgo en que se halla esta población; debiéndose recelar con mayor fundamente a vista del temporal que continua sin ceder la creciente del río y que en concurso de los trabajadores con la continuación del afán y su miseria, necesitan reforzar sus fuerzas con el preciso alimento y quedar satisfechos al mismo tiempo los materiales de madera, paja, soga y otros [...] considerando la ciudad que la incesante lluvia general y continuación de la crecida puede ocasionar mayores recelos la noche de este día con la inundación, deseando vigilar sobre el remedio con el resto de sus fuerzas y la asistencia de mayor número de caballeros capitulares, acordó se forme escala para esta concurrencia*".

Doc. 4: Murcia on September 10, 1733 (*MCB of 1733. MMA)*: "*tratar de conferir y resolver el medio de reparar los innumerables daños que ha ocasionado la crecida del río Segura que sobrevino el 6 del corriente [...] entre los muchos estragos que a causado ha sido uno de los de mayor consideración haber quebrantado el trenque del Chillerón en el río de Sangonera [...] como también la nueva fortificación del principalísimo edificio del malecón, cuyos quebrantos ha hecho patentes la elevación la elevación de las aguas en aquel sitio manifestando lo mismo en las murallas del arenal hasta el puente de madera el que ha quedado intransitable debiéndose ocurrir con la misma vigilancia al terraplén del camino de la puerta de Orihuela, quijeros del río Viejo que ha destruido en su entrada se le da trascendencia el celo de esta ciudad a providencias el reparo de la acequia mayor de Aljufia que ha quebrado por distintas partes [...] la ciudad habiéndolo oído con las demás particulares noticias que han expuesto en su lugar cada uno de los caballeros que componen este consistorio dignas de la mayor atención por la evidencia de los innumerables daños que se han seguido: pueda con el dolor que corresponde a este impensado accidente, el que ha lastimado la mayor parte del vecindario; de esta huerta llevándoles los esquilmos pendientes de panizo, vino, frutas y hortalizas, linos y otros, destruyendo los palacios y demás habitaciones, sacando de ellos con voracidad el trigo, cebada, paja y demás prevenciones reservadas para su alimento y el de sus averíos ahogándose parte de ellos y otros [...] reabriendo las acequias, brazales, regaderas y escorredores, arruinando los puentes, maltratando los caminos, sendas y veredas, dejando muchas tierras sin uso y por consiguiente infructuosas; siendo tan furioso el ímpetu de la avenida que además de haber quebrado la acequia mayor de Aljufia uno de los vasos que dan riego a la mitad de la huerta le ha dejado a la de las Barreras luego con el depósito de tarquín imposibilitando el curso del agua para el beneficio de las tierras; ha levantado con tenacidad muchos morerales y barracas que patentemente se vieron venir por sobre las corrientes siendo estas tan eficaces en sus elevaciones que se empezaron a introducir por distintas partes de esta población, no obstante las prontas providencias que se aplicaron para contener con fajinas y estacadas este último golpe: siendo el más doloroso para esta ciudad lo extremado de sus propios y rentas y los ningunos caudales para poder acudir a contener y reparar tanto riesgo a que se halla expuesta esta capital si sobreviniere otra avenida, que se debe temer por lo inmediato del invierno; hallándose sus vecinos sus vecinos constituidos en la última miseria por las repetidas faltas de cosechas a que se les ha agregado esto impensado quebranto, sin quedarle arbitrio para subsanar por medio alguno el reparo de estos perjuicios ni más consuelo en tan continuados daños, que el de exponerlos a los reales pies de su majestad para que atendidos de su real clemencia se sirva conceder a esta ciudad los alivios proporcionados a tanta fatiga*".

Doc. 5: Murcia on September 12, 1733 (*MCB of 1733. MMA)*: "*misa solemne por habernos librado Dios de la inundación*".

Doc. 6: Murcia on September 30, 1733 (*MCB of 1733. MMA)*: "*todos los vecinos pongan luces en sus casa la noche de este día y que los caballeros comisarios de los puestos del río, los ocupan luego con los oficiales de las compañías de parroquias y demás gente que fuese necesaria para los trabajos que ocurran en las fajinas y demás que se pueda ofrecer a preservar esta población de cualquiera inundación y que los maestros albañiles carpinteros, sus oficiales y peones acudan luego a las casa de su señoría con legones, azadas y demás herramientas para distribuirles las ordenes convenientes*".

Annex C

Main text in historical documents on the flood of Santa Teresa in 1879

Doc. 1: Murcia on October 15, 1879 (*El Diario de Murcia. MMA*): "*Día de luto, sí, día de luto para Muria el día de hoy. En esta noche pasada, la avenida más terrible del rio que se ha conocido, ha destrozado con sus negras, mugientes, y pestíferas olas, inmensas riquezas, y, ¡Dios sabe!, las víctimas que abra, causado. No es posible, a la hora que escribimos, calcular las desgracias que habrán ocurrido en la huerta; pero ahora cuando la ciudad está inundada, toda el agua hace retemijiar el Puente; cuando esta mas alto el nivel del rio que piso el del Arenal, ¿cómo estará la huerta? ¿Cuántos infelices habrán perecido, sin socorro? Desgraciadamente deben ser muchos [...]*

Doc. 2: Murcia on October 18, 1879 (*El Diario de Murcia in MMA*): "*Nos hemos salvado murcianos, España ha oído nuestra voz y nos socorre [...] la Gaceta de Madrid publica un decreto abriendo una subscripción Nacional para socorrer a Murcia" [...] "las pérdidas de la huerta de Murcia, bien calculadas, en casas destruidas, animales muertos, aperos de labranza perdidos, tierras que hay que roturar, esquilmos, frutos, muebles, caminos que hay que abrir, acequias que hay que renovar, vías y caminos que levantar, tierras que sanear y lo que en este momento no se nos ocurre, ¡Oh, España!, no baja de 150.000 millones"* (150.000 millones de pesetas, la moneda de la época, sería una cantidad aproximada de 900 millones de euros).

Doc. 3: Murcia on October 18, 1879 (*El Diario de Murcia in MMA*): "*Las pérdidas materiales consideradas para la huerta de Murcia, según cálculos aproximados, es de 200 millones, si bien esta cifra aumentaría el doble si los sedimentos arrastrados por las aguas y depositados en los bancales son de malas condiciones en cuyo caso secarán el arbolado*".

Doc. 3: Murcia on October 24, 1879 (*El Diario de Murcia in MMA*): "*una de las obras que más podrían contribuir a evitar que las grandes masas de agua que se forman por las lluvias torrenciales en los montes de la provincia de Murcia, es la construcción del proyectado canal de Cieza, que recogerá las aguas desbordadas, fertilizando con ellas terrenos hoy casi incultos*".

Doc. 4: Murcia on October 25, 1879 (*El Diario de Murcia in MMA*): "*Lo que se llama la "cuestión social" se presenta en Murcia en toda su pavorosa trascendencia. Hay en la huera millares de jornaleros sin pan y sin trabajo, hay millares de familias sin hogares [...] nadie cree que tiene el deber de tener hambre, nadie quiere resignarse a dormir a la intemperie y en el suelo húmedo, nadie se aviene a ir desnudo. He aquí la cuestión social: especie de gangrena de las modernas sociedades que se presenta en todas las desgracias de los pueblos. Y gracias que el colono de nuestra huerta no está estimulado por los incentivos que tiene el obrero de los grandes centros fabriles, o de las grandes capitales. Nuestro huertano es sobrio y morigerado hasta lo increíble; con un pedazo de pan y unas legumbres trabaja todo el día; con un poco de esparto se calza; con un poco de lienzo se viste, y con una inmensa fe en Dios y en la Virgen se alegra su corazón y vive los días plácidos y venturosos de las faenas agrícolas, con la sencillez de los antiguos patriarcas. Pero, a pesar de esto, decimos que está planteada la cuestión social, la cual hay que atender de modo que las medidas que se adopten no dejen rastro alguno en la población de la huerta. Cuanto antes, hay que suprimir el rancho, e inmediatamente que sea posible suspender el reparto del pan. El pan y el rancho no pueden dejar de ser una limosna, que si al principio se recibe con vergüenza, se regatea después, y se concluye totalmente por exigirse con descaro. Urge pues socorrer con trabajo, que es el socorro más noble, el que dignifica al hombre (librándole de la vagancia é impidiendo que se disipen en su corazón las nociones del bien y los sentimientos religiosos). A esa junta suprema de esta ciudad, compuesta de casi todas las corporaciones y autoridades, toca acelerar los momentos de resolución de esta suprema crisis, para que el mas enrome de la inundación no sea semillero de nuevos y mayores males*".

Doc. 5: Murcia on October 28, 1879 (*El Diario de Murcia in MMA*): "*A Los pobres: no murmuréis. Todos los socorros son para vosotros y vosotros los recibiréis. Nadie os quitará nada: tened paciencia [...] si no tenéis paciencia y resignación los pobres, no seréis dignos de caridad. Cuando por amor de Dios se da una limosna, se quiere dar a los buenos, no a los viciosos, no a los que no han perdido nada, porque ya lo tenían todo perdido*".

Doc. 6: Murcia on April 10, 1880 (*El Diario de Murcia in MMA*): "*A quienes nos escriben anónimos: No sabemos ni podemos figurarnos quiénes son estos. Algunos nos parecen amigos, otros no lo parecen. Los más nos* *exigen que escribamos en EL DIARIO con arreglo al criterio suyo. Unos nos llaman volterianos é incrédulos, otros teocráticos y amigos de los curas. Unos nos excitan que combatamos al alcalde, al ayuntamiento, y otras autoridades; otros nos rechazan las palabras de elogio que tenemos para el gobernador*".

Doc. 7: Murcia on December 7, 1879 (*El Diario de Murcia in MMA*): "*Lo justo sería, en la distribución de los donativos, indemnizar todos los perjudicados que ha habido, en la proporción que fuera posible. Para esto no debe haber clases, ni distinción, entre propietarios y jornaleros*" [...] "*hemos llamado la atención de la juntas sobre la propiedad urbana, pues estos propietarios se ven reducidos a una miseria vergonzante, más difícil de conllevar que la pobreza resignada y conocida*" [...] "*Respecto de las habitaciones de la huerta, creemos que el problema de su propiedad no debe ser obstáculo para su construcción; porque lo cierto y verdad es, que sean palacios, que sean barracas, que sean chozas, la población rural de la huerta viene disfrutando de generación en generación todos los albergues. Las casas o barracas deben hacerse donde estaban; allí sirven las tierras, allí albergan cómodamente los labradores, allí han de disfrutarlas siempre. Así como la inundación no preguntó de quien era para destruirlas, así la caridad no ha de preguntar de quien son para levantarlas. Por otra parte, la propiedad de la huerta está tan dividida y subdividida, que para cien propietarios ricos acaudalados que haya, hay diez mil pobres, que obtienen una mezquina renta de la tierra*".

Doc. 8: Murcia on January 7, 1880 (*El Diario de Murcia in MMA*): "*En la zona inundada hay más de 50.000 personas, y de ellas 30.000 afligidos [...] Luego vamos a dar hogar al desvalido, para lo cual esta Junta construirá 200 casas y 200 barracas, e indemnizará la construcción de 2.000 más [...]. En la vega de Murcia las casas destruidas ascienden a 2.611 y las barracas a 314, las deterioradas a 423 y 1.047 respectivamente [...]. Los perjuicios que han sufrido las tierras inundadas ascienden a 591.622 pesetas, que con 2.753.000, valor de las viviendas y otros daños, forma un total de más de 8 millones de pesetas*".

Doc. 9: Carta que en el diario el Semanario, dirige el diputado nacional y general Manuel Cassola a otro diputado (*El Semanario in MMA*): "*Mi querido General, los huertanos de este hermoso y desventurado país, tienen ya, los más desvalidos, trabajo que ejecutar, donde poder ganar el pan nuestro de cada día; todos ellos se encuentran vestidos, no obstante, pequeñas lagunas, casi como el día antes de la inundación. Muchos tienen sus viviendas levantadas, a otros se les están levantando, y a los demás se les levantaran en un término breve, según todas las probabilidades. El agua para el riego corre por las acequias, y los escorredores y azarbes mondados sanean el terreno y eviten la corrupción de la atmósfera respirable. La salud es buena, y la cosecha de la seda, con que comienza las labores del año nuestro inteligente y bravo huertano, ha comenzado ya con las halagüeñas esperanzas de siempre, esperanzas que endulzan los pasados sinsabores, alientan en el presente trabajo, y predisponen para el porvenir. Solo le falta una cosa para creerse y considerarse regenerado: lo sangre de toda industria; el capital circulante, dinero. Pero ¿es que carece de él verdaderamente o que no se lo quieran dar?-No me toca responder a esta pregunta, la competencia de la respuesta es de ustedes, de la Ilustre Junta de Señores Diputados y Senadores, que reside en Madrid. —Yo espero confiado la siguiente contestación, que salva por completo a mi país: «lo tiene y se lo va inmediatamente repartir»".*

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FEATURES OF WEATHER TYPES INVOLVING HEAVY RAINFALL ALONG THE SOUTHERN SPANISH MEDITERRANEAN

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ABSTRACT. Heavy rainfall events in the Mediterranean can be of high intensity, commonly exceeding 100 mm day^{-1}, and have irregular spatio-temporal distribution. Such events can have significant impacts both on soils and human structures. The aim of this paper is to highlight a systematic comparison of synoptic conditions with heavy rainfall events in Mediterranean Southern Spain, assessing the weather types responsible for meteorological risk in specific locations of this mountainous region. To do this, we analyzed the maximum intensity of rainfall in observational periods ranging from 10 min to 24 h using a database from 132 rain gauge stations across the study area since 1943; then, the heavy rain has been associated with the weather type which triggers it. This analysis identified a pattern of heavy rainfall which differs from that previously reported in the Mediterranean area. Thus, in this research, the maximum number of heavy rainfall events uses to come from a dominant pattern of low pressures associated to front systems and East-Northeast winds; but the maximum volumes use to be associated to Cold Drops and the same winds; in addition, there are differences throughout the territory, showing several patterns and seasonal incidence when analyzing sub-zones, which may be related with different erosive conditions according to its position with respect to Atlantic or Mediterranean sea, and the entity of its relief.

Características de los tipos de tiempo que implican precipitaciones intensas a lo largo de la España sur mediterránea.

RESUMEN. Los eventos de fuertes precipitaciones en el Mediterráneo pueden ser de intensidad alta (superando habitualmente los 100 mm día^{-1}) y tener una distribución espacio-temporal irregular. Estos eventos también pueden tener impactos significativos en los suelos y en las infraestructuras. El objetivo de este artículo es plantear una comparación sistemática de condiciones sinópticas con eventos de fuertes lluvias en la España sur mediterránea, evaluando los tipos de tiempo responsables del riesgo meteorológico en localizaciones específicas de esta región montañosa. Para lograr este objetivo, se analiza la intensidad máxima de precipitación desde 1943 en un periodo de observación de 10 minutos a 24 horas usando una base de datos de 132 estaciones meteorológicas. Posteriormente, la lluvia intensa se ha asociado con el tipo de clima que la desencadena. Este análisis identificó un patrón de fuertes lluvias que difiere del conocido con anterioridad en el área mediterránea. En consecuencia, en esta investigación, el número máximo de eventos de lluvias intensas suele ocasionarse a partir de bajas presiones asociadas a sistemas de frente y vientos del Este-Noreste, pero los volúmenes máximos suelen estar asociados a Gotas Frías y a los mismos vientos. Además, existen diferencias en todo el territorio, mostrando varios patrones e incidencia estacional al analizar subzonas, que pueden estar relacionadas con diferentes condiciones erosivas según su posición respecto al Atlántico o Mediterráneo y la entidad del relieve.

Key words: Heavy rainfall, Mediterranean, Synoptic Weather Situation, Climate Change.

Palabras clave: precipitaciones intensas, Mediterráneo, Simulación sinóptica del tiempo, cambio climático.

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1. Introduction

Heavy rainfall events in the Mediterranean can be of high intensity and irregular spatio-temporal distribution (Romero *et al.,* 1999; Llasat, 2001; Peñarrocha *et al.,* 2002; Beguería *et al.,* 2009). They commonly involve rainfall exceeding 100 mm h^{-1}, and sometimes reach levels exceeding 375 mm h^{-1} (Camarasa, 1994), and it is not unusual for the annual average to be exceeded by factors of two or three in single events (Gil Olcina, 1989).

These events have hydrological, territorial, economic, and social consequences, and detrimentally affect the quality of life of affected communities. From the hydrological point of view the rainfall levels are critical as they affect the rainfall-to-runoff relationship, impacting the initial infiltration capacity of the soil and runoff thresholds and coefficients (Yair and Lavee, 1985; Camarasa and Segura, 2001; Cammeraat, 2004; Rodrigo Comino *et al.,* 2016; Camarasa *et al.,* 2020), and often result in flash floods.

The increased risks associated with heavy rainfall events are not only environmental, but increase the vulnerability of affected communities, particularly under the effects of climate change (IPCC, 2001, 2007, 2014, 2019). Changes in the water cycle, hydrological patterns, and climatic patterns are of great concern to affected populations, and consequently are receiving increased research attention (Guijarro Pastor, 2002; Katz *et al.,* 2005; Negri *et al.,* 2005; De Luis *et al.,* 2010; Coscarelli and Caloiero, 2012; Lemus and López, 2016; Olcina, 2017). These changes affect economic activities (including agriculture, energy production, and drinking water supply) and natural risks (including dry spells, floods, and landslides) (Hennessy and Pittock, 1995; Ferrari *et al.,* 2013; Martínez Navarro, 2018).

This process is an indicator of current climate change, as Mediterranean societies have historically adapted to changes in resources and risks (Butzer, 2005), and have remained resilient to past fluctuations in the magnitude and intensity of extreme weather episodes. However, the current situation may herald major impacts on natural and anthropic aspects of water resources in Mediterranean areas.

The increasing number of days exceeding the long-term average maximum and minimum temperature in Mediterranean environments (Barcena *et al.,* 2018) is causing the energy accumulated in the system to intensify the hydrological cycle, and so increase the number of extreme high intensity rainfall events, which in turn result in a greater number of catastrophic floods (European Environment Agency, 2018a), with their attendant risks.

An important issue is the definition of a heavy rainfall event. These are considered to be characterized by high intensity and having the capacity to generate significant impacts on and changes in affected areas (Martín and Llasat, 2000). However, because of various meanings of the term 'extreme event', diverse definitions of heavy rainfall events have been in use in recent decades (Schumm, 1980; Palmer and Ralsanen, 2002; Trenberth *et al.,* 2015). Among these, the definition of Beniston *et al.* (2007) includes that for an event to be considered extreme, three main criteria must be met: rarity, intensity, and severity. For the entire Spanish territory an extreme event has been defined by Martín Vide (1989) as one generating rapid, excessive and short-lived surface runoff, involving at least 100 mm 24 h^{-1} (Santos Deltell, 1991; Olcina Cantos, 2000; Senciales and Ruiz, 2013). According to the State

Meteorological Agency of Spain (AEMET, 2013), this equates to 60 mm h^{-1} or greater. However, variability in rainfall measurement at the national level requires a better definition of heavy rainfall. Hence, Olcina Cantos (2000) identified the need to establish a new rainfall threshold that corresponds to historical severe physical or human consequences.

Knowledge of the amount and intensity of rainfall is important in the Mediterranean area (Alpert *et al.,* 2002; Olcina, 2017); thus, in some cases geomorphological rainfall has been defined as being of very high intensity and short duration, with the ability to modify the land (Sillero *et al.,* 2019). The consequences of increasing rainfall intensity are worse in this environment, where the impacts of human activities have been substantial in recent centuries. The European Environment Agency has confirmed an increase in heavy rainfall in the north and northeast of Europe but has reported diverse trends in the southern Europe (European Environment Agency, 2018b).

The records of rainfall differ according to the time scale used for the observations (Waymire and Gupta, 1981; Valdés *et al.,* 1985; Jebari *et al.,* 2007; Dunkerley, 2008), increasing its intensity and irregularity according to the reduction of the observation time interval. However, Sillero *et al.* (2019) noted that the most appropriate time interval to measure the intensity of rainfall is not clear, and that it can differ according to the type of phenomenon being investigated, the scale at which it is produced, and the specific objectives of the research. For example, basin-scale processes depend on the occurrence of specific episodes of rainfall (Cammeraat, 2004; Conesa García, 2005), and hydrological connectivity (the continuity of water flow in the basin from the headwaters to the outlet) in the particular morphoclimatic context (Bracken *et al.,* 2013). In humid environments the basal flow and the antecedent humidity are important, while in semi-arid environments the duration and intensity of the rain episodes are major factors, especially when the duration of a rainfall event is greater than the run-off concentration time of the basin or when the intensity of the rainfall is very high (Yair and Kossovosky, 2002; Yair and Raz-Yassif, 2004; Bracken *et al.,* 2008).

According to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, daily rainfall records are insufficient for studying heavy rainfall in Mediterranean areas (Hartmann *et al.,* 2013), and that more finer time scales are needed (Bengtsson and Milloti, 2010; Monjo, 2016). Empirical studies carried out by Camarasa-Belmonte and Soriano (2014) have shown that many natural processes in Mediterranean environments are related to rainfall intensity on time scales of less than 24 h. This feature is also highlighted by Rodrigo *et al.* (2019). Consequently, some studies (Bengtsson and Milloti, 2010) have emphasized the importance of information on short-term rainfall for applied problems such as the design of stormwater drainage systems. However, in Spain there was a lack of short-term rainfall data until the creation of an automatic water information system (SAIH), and sometimes the data is of poor quality because of the distribution of measurement stations. This problem is most serious in semiarid areas, where rainfall data is usually recorded daily. Therefore, there is a need to use mathematical models to estimate rainfall intensity at shorter time scales (hours, minutes), based on reprocessing of daily data (Salson-Casado and García-Bartual, 1998; Bacchini and Zannoni, 2003; Egozcue *et al.,* 2006; Rusjan *et al.,* 2009), even though such modeling can overestimate or underestimate some parameters (Bengtsson and Milloti, 2010). However, it is essential to study rainfall intensity at various scales to determine which are the most representative, to identify how the maximum values of each time scale are spatially distributed, and to evaluate which have the main geographical effects.

A second issue stems from the fact that in southern Spain, heavy rainfall phenomena may result from the Mediterranean and Atlantic (across the Strait of Gibraltar) rainfall patterns (east and west patterns, respectively). This duality has been analyzed in general terms in numerous studies (Pons and Soriano, 1994; De Luis *et al.,* 1997; Pascual *et al.,* 2001; Martin Vide, 2004; Llasat *et al.,* 2005; Neppel *et al.,* 2007; Rodrigo and Barriendos, 2008; Lana *et al.,* 2009; Turco and Llasat, 2011; Senciales-Gonzalez and Ruiz-Sinoga, 2013), along with the episodic atmospheric dynamics that affect these patterns (Martín *et al.,* 2006; Martin Vide *et al.,* 2008; Camarasa *et al.,* 2010, 2018, 2020).

The systematic comparison of synoptic situations associated with heavy rainfall events enables analysis of the weather conditions increasing meteorological risk in specific locations, as it is evident that topography affects atmospheric circulation (Hartung *et al,* 2019), especially in areas such as the Mediterranean slope (Santos-Muñoz *et al,* 2020), where the height of the landforms commonly exceeds 1000 m over short distances.

Numerous studies have investigated mesoclimatic features affecting the Mediterranean climate. The studies of Elías and Ruiz (1979), Font Tullot (1983), López Gómez (1969, 1983), Albentosa (1991), and Capel Molina (2000) on the general climate of the Iberian peninsula are important, and draw attention to the particularities of some places in the Mediterranean, especially those including the eastern zone, where catastrophic rainfall events reoccur in a phenomenon that has been referred to as "the supposed monsoon of the Iberian Peninsula" (López Gómez, 1969). In the eastern Mediterranean area, the dynamics and trends of convective rainfall episodes have been extensively analyzed (Millan *et al.,* 2005; Estrela *et al.,* 2006), including their association with unusual increases in temperature (Miro *et al.,* 2015). However, the Mesoscala convective systems (Zipser, 1982) depend on different flows in the Alboran Sea (Xoplati *et al.,* 2012; Senciales-González and Ruiz Sinoga, 2013; Ruti *et al.,* 2016).

In this study we analyzed the maximum intensity of rainfall in observation periods ranging from 10 min to 24 h in a particularly sensitive area in the southern Iberian Peninsula, and the dominant types of weather which are responsible. The study objectives were to assess the characteristics of heavy rainfall events at various time scales, its seasonal and geographic variability, and the meteorological conditions involved.

2. Methods and study area

The major heavy rainfall events recorded in southern Spain were analyzed based on the two main official databases: the Spanish Meteorological Agency (AEMET) database and that of the Alert System and Hydrological Information (SAIH) network of Spain.

First, it is necessary to clarify two concepts: “event” and “case”. i) An event is a weather situation, generalized or not, that involves heavy rain. ii) A case is the rainfall data registered by a weather device, in which it has exceeded a particular volume or intensity (100 mm 24 h^{-1}; volume in 1 h; volume in 10 min).

We analyzed 83 events and 203 cases of rainfall exceeding 100 mm in 24 h, 44 events and 90 cases of rainfall exceeding 20 mm h^{-1}, and 44 events and 90 cases of intense rainfall lasting <10 min. It has been used data from 132 rain gauge stations since 1943 to 2019.

Thus, there have been 84 events with >100 mm 24 h^{-1}; 40 events with <100 mm 24 h^{-1} but high hourly intensity; and 44 events with high intensity in 10 min. Given that some events registered as >100 mm 24 h^{-1} had also high hourly intensity (and were registered as <100 mm 24 h^{-1}) at other stations or areas, in total we analyzed 114 events (Table 2), because some events are recorded with the three type of intensity. Thus, in these cases, an event is characterized by several cases through the same or different area.

We developed a database recording events, season, and event dates. In addition, rainfall events of 10 min not only recorded maximum intensity during 10 min, but also were contrasted with the total amount of rainfall during the hour and day which did occur.

We identified six zones on the Mediterranean slope in southern Spain, based on their distances from the Atlantic Ocean and their topographical characteristics (Fig. 1).

1. (R) Campo de Gibraltar, the Ronda Mountains and the west coast of Málaga province (from Calaburras Cape to Manilva).

2. (G) Guadalhorce Valley, the central coast of Malaga province (from Calaburras to Málaga) and the west slope of Montes de Málaga.
3. (A) Axarquía shire.
4. (S) The semiarid zone of the Granada and Almería provinces.
5. (N) Sierra Nevada (Granada-Almería, >1000 m height).
6. (D) The sub-desert domain of Almería.

Each event was associated according to four characteristics: i) ground level weather situation, ii) 500 hPa level weather situation, iii) dominant ground-level wind, and, iv) 500 hPa level winds. On this basis, weather types were classified and related to the rainfall volumes and number of cases, and to statistical estimators. Events and cases were distinguished: thus, an event involving heavy rainfall may have been recorded at only one weather station (one event with only one case), or at several stations (one event with several cases).

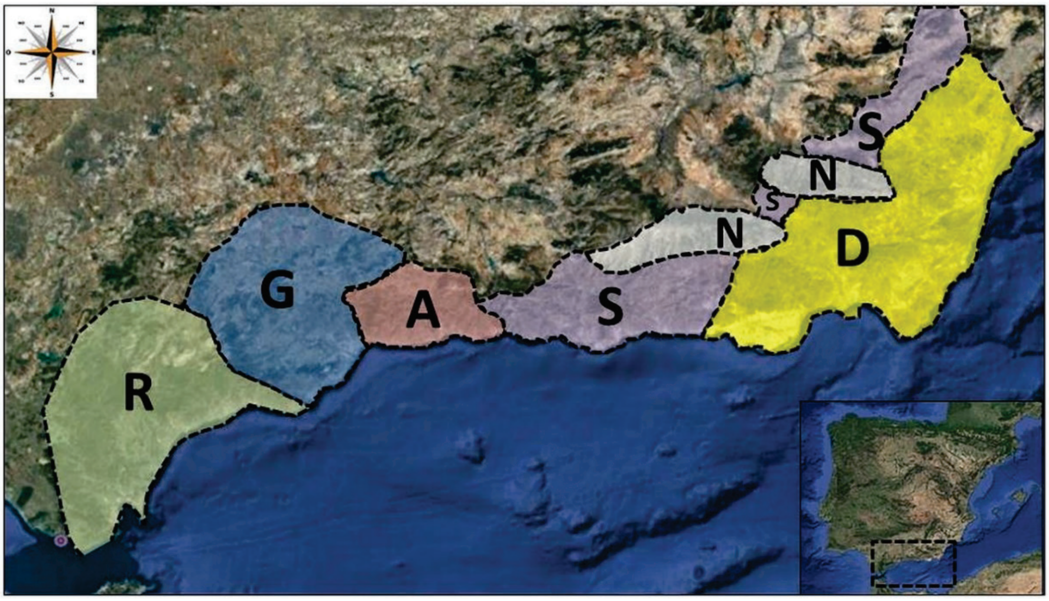


Figure 1. Study area. R: Campo de Gibraltar, Ronda Mountains and West Coast of Málaga province. G: Guadalhorce Valley, central coast of Málaga province and West slope of Montes de Málaga. A: Axarquía shire. S: Semiarid zone of Granada and Almería provinces. N: Sierra Nevada (Granada-Almería, >1000 m). D: Subdesert domain of Almería.

Six weather types were identified (Rodrigo *et al.,* 2020):

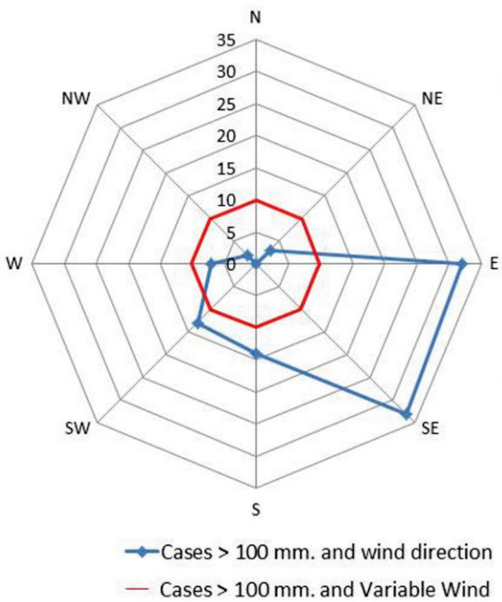
1. Dynamic low pressure without fronts (DL): dynamic low-pressure events lacking associated fronts throughout the complete event.
2. Cold air pool (CD): weather systems involving cold-air damming at height, but without low pressure at ground level. Thus, any element with a positive surface pressure (> 1014 hPa) linked to an isolated cold air cell at height was classified as a CD.
3. Thermal low pressure (TL): these are rainfall events which occur in summer or close to summer characterized by low pressure at ground level, but height values higher than 5520 m. at 500 hPa levels. They may or may not be associated with frontal systems.

4. Weak Anticyclones or Weak Low-pressure weather systems (WA-D): It is usual that barometric swamps evolve in a few hours to local thermal low pressure or let the arrival of moisture-laden air from the sea. They involve an undefined field of pressure that is sometimes linked to heavy rainfall; they lack frontal systems.
5. Dynamic low pressure with fronts (DL+F): dynamic low-pressure weather systems that show instability in all atmosphere levels. The frontal system determines the precipitation period, and up to three fronts may occur during the same event.
6. High pressure weather systems with fronts (A+F): high pressure systems associated with unstable air masses, especially those of maritime origin and in contact with masses having different characteristics (temperature/humidity). In these cases, the high-pressure systems show internally levogyrous curvature coincident with respect to the fronts.

These weather types were analyzed on the basis of four rainfall levels as follows.

A. Average rainfall >100 mm 24 h^{-1}, and events distributed over the study area.
B. Average rainfall <100 mm 24 h^{-1} and >20 mm in one hour, and events distributed over the study area.
C. Hourly average rainfall >20 mm during events (regardless of the total volume), and events distributed over the study area.
D. Average 10-minute rainfall rate during events >20 mm h^{-1}, and total amount of 10-minutes rainfall compared with total amount of hourly rainfall events (10-minutes rainfall * 100 / 1 hour rainfall).

The weather types and rainfall were related to the surface wind direction. Based on cause and regional origin, five wind direction groups were identified: NE-E (winds from the Mediterranean basin); SE-S (from Alborán and Africa); SW-W (from the Atlantic Ocean); N-NW (continental winds); and Variable (winds variable during the event) (Fig. 2).



Wind dir.	Num. of events
N	0
NE	3
E	32
SE	33
S	14
SW	13
W	7
NW	2
Variable	10
TOTAL	114

Figure 2. Number of events having rainfall >100 mm 24 h^{-1}, and wind directions.

3. Results

3.1. Average rainfall >100 mm 24 h^{-1}, and events distributed over the study area

More than 50% of rainfall events >100 mm h^{-1} affecting the entire study area were associated with the DL+F weather type and NE-E winds, the CD weather type and NE-E winds, and both DL+F and CD weather types and SE-S winds (Fig. 3).

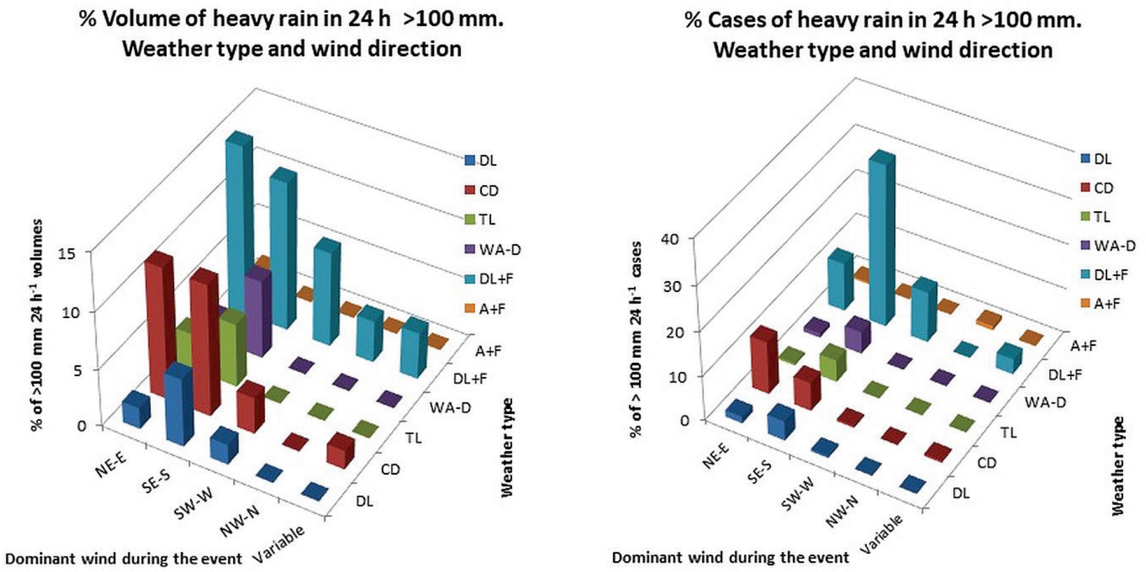


Figure 3. Volume and case percentages of average rainfall >100 mm 24 h^{-1}.

Most frequently events having average rainfall > 100 mm 24 h-1 were associated with the DL+F weather type and SE-S winds (36% of cases), and secondarily with the CD weather type and NE-E winds, the DL+F weather type and NE-E winds, and the DL+F weather type and SW-W winds. These four weather types comprised 70% of the cases. This indicates that several weather types associated with a few cases involved large precipitation volumes, particularly any weather type associated with SE-S winds, or any wind associated with the DL+F weather type.

There were differences with respect to precipitation volume and the number of cases in each zone.

Maximum rainfall volumes in the semiarid zone of Granada and Almería (hereafter, "the S zone") were associated with NE-E winds and the DL+F weather type; but the maximum frequency occurred in the Guadalhorce valley ("the G valley") associated with the CD weather type.

SE-S winds were also associated with maximum rainfall volumes in the S zone, but in this case associated with the CD weather type. In contrast, by far the greatest frequency of cases occurred in the Campo de Gibraltar-Ronda mountains (hereafter, "the R mountains").

Maximum rainfall volume in the sub-desert area of Almería (hereafter, "the D area") was associated with SW-S winds and the CD weather type, but this involved only a single case. Apart from this, the maximum average precipitation volume in the R mountains was associated with the DL+F weather type. With respect to the number of cases, the maximum frequency in the R mountains and the S zone was associated with the DL+F weather type.

In only two cases were NW-N winds linked to the DL+F weather type, one in the R mountains, and the other in the S zone.

Variable winds were associated with maximum rainfall values in the R mountains but involving only a single case associated with the DL+F weather type. Apart from this exception, the maximum precipitation average volume occurred in the D area associated with the DL+F weather type, the same area that was associated with the maximum case frequency.

3.2. Average rainfall <100 mm 24 h^{-1} and >20 mm in one hour, and events distributed over the study area

The maximum percentage of average rainfall events <100 mm 24 h^{-1} and >20 mm in one hour distributed over the study area was associated with the A+F weather type and NE-E winds. A similar percentage were associated with the CD weather type and NE-E winds, and the DL+F weather type associated with SE-S winds. These three weather types accounted for more than 50% of the rainfall events <100 mm 24 h^{-1} and >20 mm on one hour (Fig. 4).

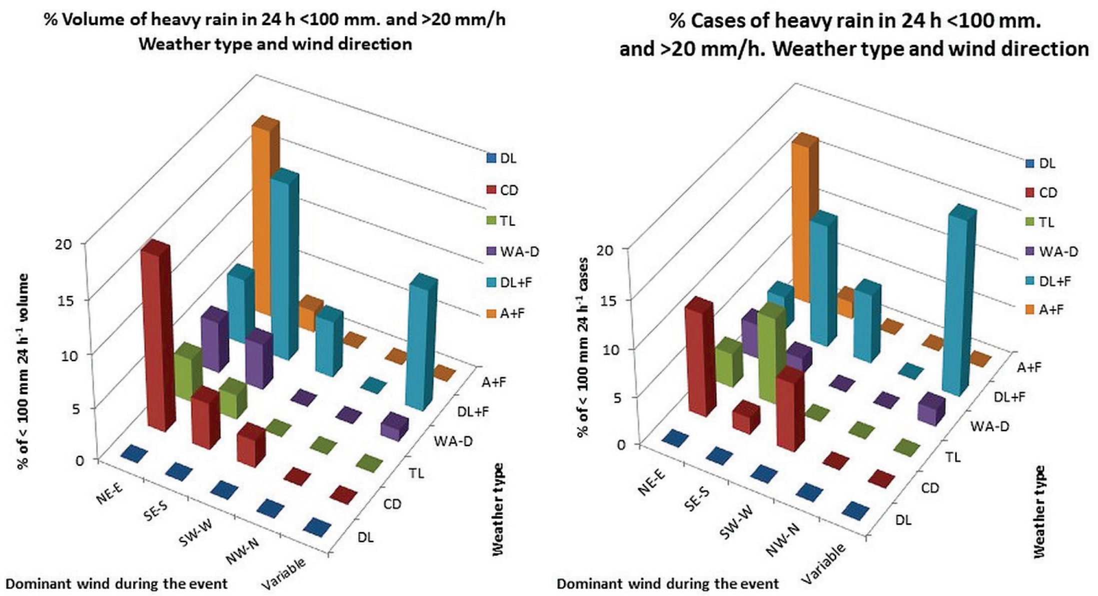


Figure 4. Volume and percentage of cases of rainfall events <100 mm 24 h^{-1} and >20 mm on 1 hour.

However, the case frequencies differed, with the most frequent rainfall events <100 mm 24 h^{-1} and >20 mm on one hour being associated with the DL+F weather type and Variable winds (18% of cases), and less frequently with the A+F weather type with NE-E winds, the DL+F weather type with SE-S winds, and the CD weather type with NE-E winds. Together, these four weather types comprised 58% of the cases. This indicates that there were several weather types involving few cases but with high precipitation volumes. For any weather type associated with NE-E winds, or the DL+F weather type associated with SE-S winds, higher rainfall volumes were involved in a few cases of rainfall events <100 mm 24 h^{-1} and >20 mm in one hour.

There were differences with respect to the volume and number of rainfall cases in each zone. Thus, NE-E winds were associated with maximum rainfall volumes in the S zone and the A+F weather type; but the maximum frequency occurred with the A+F weather type in the D area.

Maximum rainfall volumes occurred in the G valley associated with the DL+F weather type and SE-S winds. The greatest frequency of cases in the R mountains occurred with several weather types, but intense rainfall was most frequently associated with the BD+F weather type with SE-S winds.

Maximum rainfall volumes also occurred in the G valley associated with the DL+F weather type and SW-W winds. The highest frequency of cases also occurred in the G valley but associated with the CD weather type. There were no other cases recorded other than those in the R mountains and the G valley.

No cases of rainfall of an intensity >20 mm h^{-1} associated with NW-N winds was recorded, and there were no cases of the DL weather type.

Maximum rainfall occurred with Variable winds in the R mountains associated with the DL+F weather type, but the highest frequency of cases occurred in the S zone, also in association with the DL+F weather type.

3.3. Hourly average rainfall >20 mm during events (regardless of the total rainfall volume), and events distributed over the study area

The maximum percentage of rainfall events >20 mm h^{-1} in the study area were associated with the CD weather type and NE-N winds, and to a similar but lesser extent with the A+F weather type and NE-N winds, the DL+F weather type and SE-S winds, and the DL+F weather type and Variable winds. These four weather types accounted for >56% of the rainfall events >20 mm h^{-1} (Fig. 5).

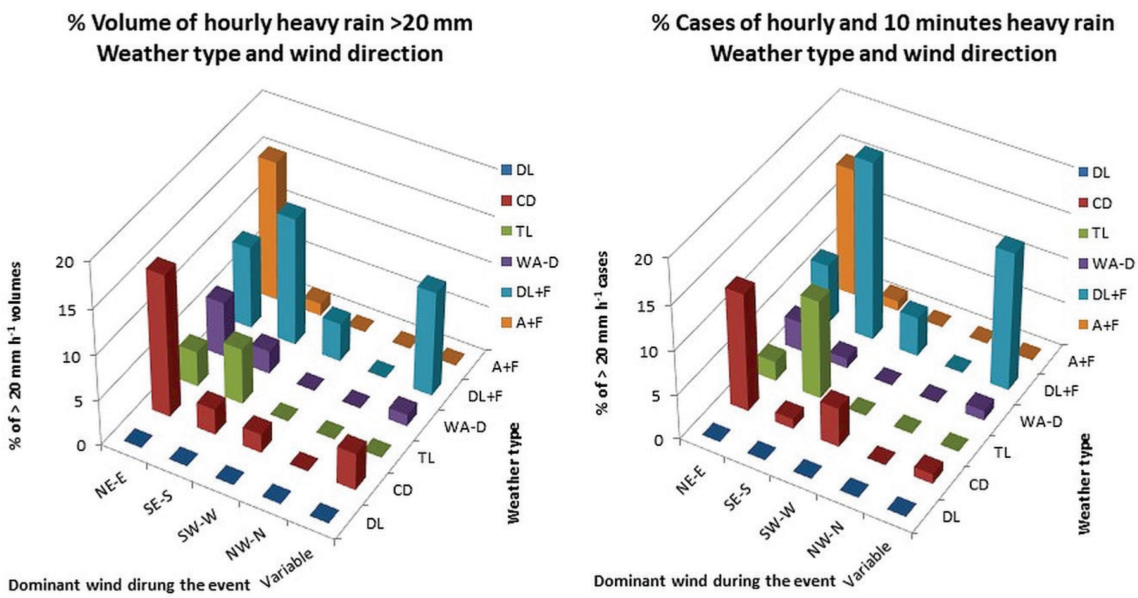


Figure 5. Volume and case percentages for hourly rainfall > 20 mm.

The case frequencies differed only slightly in this analysis. The same weather types were most frequently associated with the cases. Thus, the DL+F weather type with SE-S winds were associated with the highest number of cases, although the DL+F weather type with Variable winds, the A+F weather type with NE-E winds, and the CD weather type with NE-E winds also accounted for a high number of cases. These four weather types accounted for almost 63% of the cases, with several weather types associated with a few cases provided large precipitation volumes. Any weather type associated with NE-E winds accounted for higher volumes for cases involving rainfall >20 mm h^{-1}.

With respect to volume and number of rainfall cases in each zone, the results varied. Thus, NE-E winds associated with the DL+F weather type accounted for maximum rainfall volumes >20 mm h^{-1} in the S zone, and also the maximum frequency.

SE-S winds associated with TL weather type produced maximum rainfall volumes in the S zone. As there were <100 mm events, the main frequency of cases in the R mountains was associated with several weather types, with the DL+F type and SE-S winds being the most frequent for >20 mm h^{-1} events.

SW-W winds showed the same relationship to rainfall events as found for <100 mm events, with maximum values associated with the G valley and the DL+F weather type, and the highest frequency of cases occurring in the G valley, but associated with the CD weather type.

When there are variable winds, maximum hourly rainfall values are reached in D area with DL+F weather type, but the highest frequency of hourly rainfall cases occurs in the S zone, also related to the DL+F weather type.

*3.4. Average 10-minute rainfall rate during events >20 mm h^{-1}, and total amount of 10-minutes rainfall compared with total amount of hourly rainfall events (10-minutes rainfall * 100 / 1-hour rainfall).*

As the analyzed cases were the same for both hourly and 10-min rainfall, this analysis was centered in the rainfall volumes fallen in ten minutes (Fig. 6).

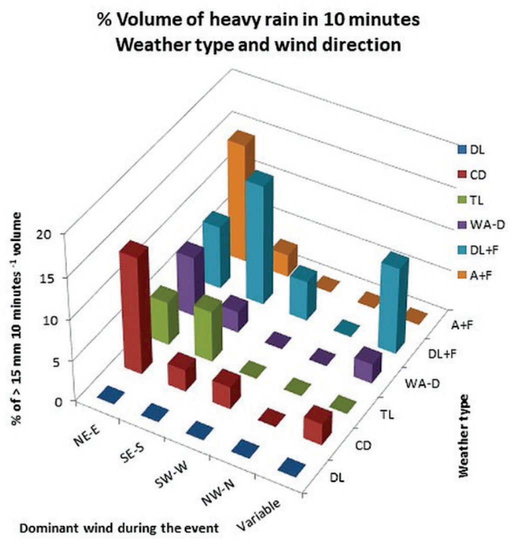


Figure 6. Volume percentages for heavy rainfall in 10 minutes related to rainfall in 1 hour.

The maximum percentage of heavy rainfall during 10 min in the study area was associated with the DL+F weather type and SE-S winds, although similar but lower percentages were associated with the A+F weather type with NE-E winds, and the CD weather type with NE-E winds. These three weather types accounted for almost 43% of the 10-min rainfall events >20 mm h-1.

Differences with respect to average rainfall volumes in each zone were as follows.

Maximum rainfall volumes in <10 minutes were associated with the CD weather type and NE-E winds in the R mountains. This shire had the highest intensity, even though the intensity in any area was usually associated with the DL+F weather type.

Maximum volumes in the S zone were associated with the DL+F weather type and SE-S winds. No area clearly showed a maximum rainfall volume, with similar values being found in the G valley, the D area, and Axarquía shire (A).

SW-W winds showed maximum rainfall values in the G valley associated with the CD weather type.

Variable winds had maximum rainfall values in the D area associated with the DL+F weather type.

3.5. Summary of rainfall intensities, weather types, and winds by zone

Table 1 and Figure 7 show the weather types and winds in relation to rainfall volume and cases for each type of intensity analysis and zone. Although there was no clearly defined pattern, some main trends were evident. Thus, the mountainous zones (the R mountains and Sierra Nevada) were dependent on the CD weather type. The DL+F weather type was common both in Axarquía (A) shire and Guadalhorce valley (G), in this case together CD weather type. The A+F, TL, and CD weather types typically occurred in oriental zones (the S zone and the D area). The eastern zone shows similar weather type frequencies to other researches relating rainfall and weather type reported in the East of Spain, including Valencia (Rodrigo et al. 2020). With the exception of Sierra Nevada (N), where NE-E winds and CD weather type were dominant for any rainfall intensity type, there was no clearly dominant wind direction explaining the rainfall intensity in any zone, although we note that there were no cases involving NW-N or SW-W winds (except in the D area).

The distribution of maximum rainfall values >100 mm 24 h-1 can be generalized as follows. The number of rainfall cases in the western area depended on SE-S winds and the DL+F weather type; on the contrary, the number of rainfall cases in the eastern area depend on NE-E winds combined with the CD and DL+F weather types. The rainfall volume depended on NE-E winds in western and eastern areas, but SE-S winds prevailed in central areas.

The distribution of maximum rainfall values <100 mm 24 h^{-1} and >20 mm h^{-1} was easily classifiable according to the rainfall volume and wind direction: SE-S winds in western areas, and NE-E winds in eastern areas. The hourly maximum rainfall volumes depended mainly on NE-E or Variable winds. There was no clear association with the frequency of cases. The 10-minute rainfall volume was dependent on NE-E winds in the mountainous areas (R and N), while the rest of the areas were dependent on SE-S winds.

Zone	Max. intensity >100 mm.				Max. intensity < 100 mm.				Max. intensity 1 h.				Max. intensity 10 min.			
	Volume		Cases		Volume		Cases		Volume		Cases		Volume		Cases	
	WT	Wind	WT	Wind	WT	Wind	WT	Wind	WT	Wind	WT	Wind	WT	Wind	WT	Wind
R	DL+F	NE-E	DL+F	SE-S	CD	SE-S	TL	SE-S	CD	NE-E	DL+F	SE-S	CD	NE-E	DL+F	SE-S
G	CD	NE-E	DL+F	SE-S	DL+F	SE-S	CD	SW-W	CD	Var.	CD	NE-E	DL+F	SE-S	CD	NE-E
A	DL+F	SE-S	DL+F	SE-S	DL+F	SE-S	(*)	NE-E	DL+F	NE-E	DL+F	NE-E SE-S	DL+F	SE-S	DL+F	NE-E SE-S
S	CD	SE-S	DL+F	SW-W	A+F	NE-E	DL+F	Var.	A+F	NE-E	DL+F	Var.	TL	SE-S	DL+F	Var.
N	CD	NE-E	DL+F	NE-E	CD	NE-E	CD	NE-E	CD	NE-E	CD	NE-E	CD	NE-E	CD	NE-E
D	TL CD	NE-E SW-W	CD	NE-E	A+F	NE-E	A+F	NE-E	DL+F	Var.	DL+F	Var	DL+F	SE-S	DL+F	Var.

WT. = Weather type; Var. = Variable wind; (*) No dominant type.

Table 1. Weather types and winds related to rainfall volume and cases for each type of intensity analysis and zone.

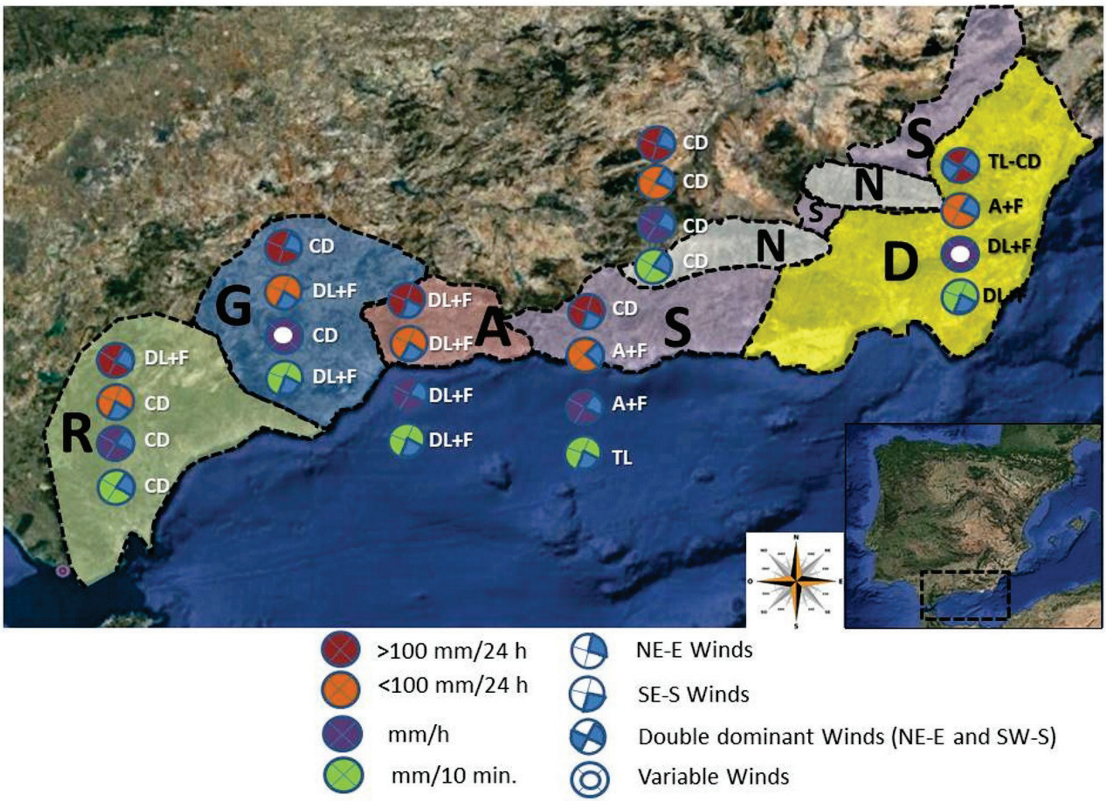


Figure 7. Weather types and wind directions in the study area during maximum intensity events.

3.6. Summary of events, cases, and volumes related to weather types

Table 2 shows the frequencies of events and cases of rainfall >100 mm 24 h^{-1} and <100 mm 24 h^{-1} (but >20 mm h^{-1}) related to weather types. This shows that even though the DL+F weather type was associated with a higher frequency of events and cases; the maximum rainfall volume was associated with the CD weather type for rainfall events >100 mm 24 h^{-1} and <100 mm 24 h^{-1}. The TL and WA-D weather types were also well represented among events >100 mm 24 h^{-1}, although the liters/case values for the TL weather type were lower. The lowest values for events and cases >100 mm 24 h^{-1} were associated with the A+F weather type (only one event and case). There were no cases of events <100 mm 24 h^{-1} associated with the DL weather type, and the minimum event and case values were associated with the TL weather type.

Table 2. Events, cases, and volume of rainfall >100 and <100 mm 24 h^{-1}.

	EVENTS >100	CASES >100	mm/event	Liters/case	EVENTS* <100	CASES <100	mm/event	mm/case
DL	6	13	166.58	169.21	0	0	0	0
CD	20	39	**201.03**	200.58	7	11	**62.72**	58.93
TL	4	11	189.99	171.33	4	7	41.37	42.53
WA-D	7	12	189.93	192.88	4	4	48.35	48.35
DL+F	46	127	186.04	187.51	19	23	56.56	55.90
A+F	1	1	126.00	126.00	6	10	60.76	62.63
	84	203			40	55		

* Because the pluviographic dataset (hourly data) period was shorter (since 1994), there were fewer cases for rainfall events <100 mm 24 h^{-1} than for events >100 mm 24 h^{-1}.

Table 3 shows the frequency of hourly a ten minutes rainfall events and cases. As in Table 2, the maximum hourly rainfall volume was associated with the CD weather type, but the maximum ten-minute rainfall values were associated with the TL weather type.

Table 3. Events, cases, and volume of rainfall >20 mm h^{-1} and 10 minutes.

	EVENTS* >20 mm h^{-1}	CASES >20 mm h^{-1}	mm/ event	mm/case	EVENTS <10 min.	CASES <10 min.	mm/event	mm/case
DL	0	0	0	0	0	0	0	0
CD	9	18	**48.54**	46.14	9	18	21.28	21.36
TL	5	12	41.27	45.43	5	12	**22.23**	23.06
WA-D	4	4	30.75	30.75	4	4	18.60	18.60
DL+F	20	42	43.35	43.89	20	42	20.49	20.74
A+F	6	14	43.88	46.46	6	14	21.72	21.82
	44	90			44	90		

* Several events had hourly values > 100 mm h^{-1}, so there were more events and cases of rainfall > 20 mm h^{-1} than for < 100 mm h^{-1}.

Table 4 shows the weather types and wind directions for ten-minute rainfall values over the study area. This shows (right hand side of Table 4) that more than a 50% of the hourly rainfall occurred in 10 minutes. Moreover, the SW-W wind direction reached the highest average rainfall ratio (rain fall in ten minutes*100/ rainfall in one hour) with a 59.6% of rainfall amount fallen in only ten minutes. However, the maximum absolute percentage was associated with the A+F weather type and SE-S winds (97.7% of the hourly rainfall fallen in ten minutes).

Table 4. Ten-minute intensity percentage with respect to hourly intensity.

	Average 10-minutes maximum intensity					% with respect hourly intensity				
	NE-E	SE-S	SW-W	NW-N	Variable	NE-E	SE-S	SW-W	NW-N	Variable
DL	0.00	0.00	0,00	0.00	0.00	0	0	0	0	0
CD	21.72	20.30	20.85	0.00	20.10	45.8	45.5	63.6	0	31.3
TL	20.10	**23.65**	0.00	0.00	0.00	72.7	49.8	0	0	0
WA-D	18.25	19.70	0.00	0.00	18.20	58.2	49.4	0	0	89.7
DL+F	19.46	22.20	18.48	0.00	20.07	45.3	51.7	56.5	0	47.8
A+F	21.90	20.80	0.00	0.00	0.00	47.1	**97.7**	0	0	0
Average	20.29	**21.33**	19.66	0.00	19.46	49.0	55.1	**59.6**	0	47.3

3.7. Seasonal high rainfall by region

Analysis of heavy rainfall events throughout the study area showed that the highest number of high intensity events (>100 mm or >20 mm h^{-1}) occurred in autumn (62.3%). However, Table 5 shows that this did not apply in all the study areas, as the high number of cases in autumn skewed the dataset to this season, especially for the R mountains. Thus, while the R mountains showed maximum percentages of high rainfall in autumn, in the G valley it occurred in winter and spring, in Axarquía shire and the D area it occurred in spring, in Sierra Nevada (N) it occurred in winter, and in the S zone it occurred in summer. The number of cases analyzed in each area ranged from 10 (N) to 48 (R).

Table 5. Seasonal distribution (%) of heavy rainfall events in each zone.

	Events	%	R	G	A	S	N	D
Summer	12	10.53	16.67	11.11	11.11	33.33	5.56	22.22
Autumn	71	62.28	37.00	24.00	8.00	12.00	5.00	14.00
Winter	24	21.05	25.00	25.00	7.14	14.29	14.29	14.29
Spring	7	6.14	12.50	25.00	12.50	12.50	0.00	37.50

4. Discussion

This study sought to address the inadequacies in Mediterranean areas of daily rainfall records for studying heavy rainfall (Hartmann *et al.,* 2013), and the need for the study of high intensity rainfall at finer time scales (Bengtsson and Milloti, 2010; Monjo, 2016). Thus, we compared the average volume associated with rainfall events greater than 100 mm 24 h^{-1} with the total annual precipitation, to determine the extent to which these events contribute to overall precipitation.

The analysis of rainfall episodes is essential in semiarid environments, because, depending on its intensity (Bull *et al.,* 1999; Hugues, 2005; Yair and Raz-Yassif, 2004; Bracken *et al.,* 2008) and scale (Yair and Raz-Yassif, 2004), an episode can affect resources or may present a risk in many different ways. It is known that in southern of Spain, the torrential nature of the rainfalls can alter the soil water availability for vegetation (Ruiz Sinoga *et al.,* 2019) but also it is able to modify the surficial component of the territory (mass movement, ravine growth, rock falls…) in addition to soil loss; then "geomorphological precipitation" has been proposed as a term which define this type of heavy rain (Sillero *et al.,* 2019).

An important issue for applied research in semiarid environments is to define the most representative rainfall indicator and the best scale for analysis. Because of the variability of the processes, it is necessary to have a series of reference observatories because the number of stations differs among areas. Thus, the R mountains area has 30 stations, the G valley has 35, Axarquía shire has 12, the S zone has 23, Sierra Nevada has 10, and the D area has 23.

As a result of the high energy and low frequency of these rainfall events in semiarid environments, those of high intensity and short duration have extremely variable spatio-temporal distribution (Romero *et al.,* 1999; Llasat, 2001; Armengot, 2002; Peñarrocha et al., 2002; Beguería *et al.,* 2009). Thus, among the events analyzed for each area, there were only 64.3% that were isolated, 11.9% occurred in six or more stations, and 10 events were general and not associated with any particular area. A characteristic of the Spanish Mediterranean area is that although the average annual precipitation is in the range 500-700 mm, a single event can exceed these values by two- or even three-fold (Gil Olcina, 1989). Thus, some events can exceed 800 mm of precipitation in a single day, as occurred in the city of Gandía in November 1987. In general, in Mediterranean environments it is very common for the rainfall intensity to exceed 100 mm h^{-1} during a storm (Camarasa *et al.,* 2010, 2014, 2020). However, in southern Spain we have no cases in the analyzed series. Of the 100 cases involving hourly precipitation data, 36 exceeded 50 mm h^{-1} and 48 exceeded 20 mm in 10 min.

The rainfall intensity data are highly valuable in southern Spain, so it is not easy to identify reference thresholds (Montesarchio *et al.,* 2009) because the rainfall characteristics differ according to the observation time scale used (Waymire and Gupta, 1981; Valdés *et al.,* 1985; Jebari *et al.,* 2007; Dunkerley, 2008; Berne *et al.,* 2009). Nevertheless, although there are differences all over the world with respect to the rainfall thresholds, there is a medium confidence about there has been an increase in the intensity of heavy precipitation events at a global scale (IPCC, 2019). It is not clear which is the most appropriate time interval to measure the intensity of the rainfall, although the study of convective cells suggests the use of intensity thresholds of 48-50 mm h^{-1} and an interval of approximately 1 h between one event and the next (Llasat, 2001).

The maximum rainfall volume recorded with NE-E winds during rainfall events of >100 mm 24 h^{-1} corresponded to a single case of Thermal Low. Apart from this, Dynamic Lows with fronts produced the highest average rainfall volumes, while cold air pools (absent in Axarquía) represented the greatest number of events. Similarly, the highest number of rainfall cases with NE-E winds occur with cold air pools; this weather type shows an average of four cases per area during each event, while it is reduced to 3.67 cases with respect to Dynamic Low with associated fronts; cold air pools accounted for half of the total cases recorded with this wind direction. Although the Guadalhorce valley had most torrential events with this type wind (especially in the form of cold air pools), the highest average rainfall volumes occurred in the semiarid region of Granada, followed by Sierra Nevada (N). The average rainfall volume reached with this wind is 200.45 mm, with an average of 2.58 cases per event and area.

In terms of natural processes and resource and risk management, we identified the appropriate work scales for the specific objectives of this research, given the dynamics of these processes in Mediterranean areas. We determined which scales were the most representative for identifying how the maximum values of each time scale were spatially distributed, and to assess the main geographical influences. To know deeply the heavy rainfall patterns may help to prevent disasters with short-term temporal scale (Seo *et al.,* 2014; Broer and Spira, 2018).

A heavy rainfall pattern was apparent, taking into account the type of weather which it generates; in addition, it differs from that reported for other Mediterranean areas including Catalonia (Martin Vide *et al.,* 2008) and Valencia (Camarasa Belmonte *et al.,* 2010, 2014). Therefore, Facing the purely Mediterranean pattern of these sites in the south of Spain (Alboran Sea) there is a contrast between the Atlantic and subtropical patterns, as previously reported by Peña Angulo *et al.* (2020). This duality has been analyzed in general terms in numerous studies (Pons and Soriano, 1994; De Luis *et al.,* 1997; Pascual *et al.,* 2001; Martin Vide, 2004; Llasat *et al.,* 2005; Neppel *et al.,* 2007; Rodrigo and Barriendos, 2008; Lana *et al.,* 2009; Turco and Llasat, 2011; Senciales-González and Ruiz-Sinoga, 2013), as has the atmospheric dynamics that is generally involved in such events (Martín *et al.*, 2006; Martin Vide *et al.,* 2008; Camarasa *et al.,* 2010, 2018, 2020; Peña Angulo *et al.,* 2020).

This duality was corroborated as follows: the maximum rainfall volume recorded with SE-S weather was 270 mm, associated with a cold air pool, an event recorded both in the semiarid region of Granada and Almería. Thus, the cold air pools generated a higher average rainfall volume, and the highest average intensity occurred in the Almería semi-desert. However, by far the greatest number of torrential events occurred with dynamic lows in association with fronts; these accounted for more than 50% of the events with this weather type and more than two-thirds of the cases. Zone A (Campo de Gibraltar, Serranía de Ronda-Marbella) had most cases of this type, with an average of 12.2 cases per event and area. The average volume of torrential rain associated with this type of weather was less than that associated with NE-E winds (183.42 mm.). However, the number of cases associated with NE-E winds was almost double, resulting in almost 5 cases per event and zone, which implies that they are more generalized. Toward the east there was a gradual decrease in the number of cases per area.

5. Conclusions

More than 50% of the heavy rainfall events recorded in Southern Spain were associated with NE-E and SE-S winds. Specifically, the greatest volumes of precipitation (>100 mm 24 h^{-1}) were associated with the DL+F weather type and NE-E winds, although the greatest number of cases occurs with this weather type and SE-S winds. For hourly intensities (with any rainfall volume in 24 h, this is, both >100 mm 24 h^{-1} and <100 mm 24 h^{-1}), the highest rainfall volumes were associated with the CD weather type and NE-E winds, and the greatest number of cases was associated with the DL+F weather type and SE-S winds. The 10-minute intensity reaches maximum rainfall volumes of cases with DL+F weather type and NE-E wind, but the highest number of cases is reached with the same weather type, but SE-S winds. Therefore, for high intensity events the incidence of depressions having very active fronts should be considered in addition to cold air pools. In addition, different types of weather determined the occurrence of heavy rainfall across the study areas in the southern peninsula. No single weather type or wind direction dominated, except for Axarquía shire (heavy rainfall was always associated with the DL+F weather type) and Sierra Nevada (the CD weather type and NE-E winds were associated with all heavy rainfall events). Moreover, high intensity rainfall events took place at various times of the year. Amongst the study areas, the generalization that heavy rainfall predominantly occurred in autumn only applied to Campo de Gibraltar-Serranía de Ronda. Finally, the intensity of 10-minute rainfall was very high, normally accounting for 50% of the high intensity rainfall that occurred in one hour, especially associated with the TL and WA-B weather types.

In Alboran sea, in southern Spain a pattern of heavy rainfall was found that differs from that previously reported for the Mediterranean area. This was because of its geographical position, very close to the Atlantic Ocean, and the conjunction of latitude and orography.

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SEA LEVEL RISE INUNDATION RISK ASSESSMENT IN RESIDENTIAL CADASTRAL PARCELS ALONG THE MEDITERRANEAN ANDALUSIAN COAST

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ABSTRACT. The general objective of this article is to present the methodological approach for the assessment of the inundation risks associated with the rise in the mean sea level for different models and scenarios of climatic change (IPCC, 2013 and Jevrejeva *et al*., 2012). The approach focuses on the assessment of the hazard, exposure and physical vulnerability of the built areas, especially the residential areas along the Mediterranean coast of Andalusia (Spain). For hazards calculation a set of tide gauges' data and climatic scenarios were analyzed to obtain future sea levels for all the spectrum of probabilities. Further, a method is proposed for mapping the probability associated with each scenario using a 5 m cell size DTM. For exposure and vulnerability assessment of built up areas, especially for residential ones, the National Cadastre, which is the most detailed set of data, have been used. Modeling the original cadastral data in a spatial database management system and their analysis through SQL sentences have made possible to identify the cadastral parcels with residential use and associated variables (area, number of residential real estate units, constructed area below ground, etc..), being therefore the cadastral parcel the spatial reference unit for mapping. The overlay of cadastral parcels and the inundation hazard maps has allowed identifying the residential cadastral parcels exposed to each climatic scenario. A method is proposed for better identification of the number of real estate units in each cadastral parcel, assuming this number as the base for residential parcel vulnerability. Finally, the risk assessment is calculated as the product of the previous variables. For the dissemination of the inundation risk assessment results, a web application (geoviewer) was developed. Results show that for the more pessimistic scenario more than 24,000 exposed cadastral parcels would be affected. Out of that, 13,000 exposed residential cadastral parcels were identified and their hazards, exposure and vulnerability calculated in order to map the final inundation risk associated with future sea levels.

Evaluación del riesgo de inundación por subida del nivel del mar para parcelas residenciales catastrales en la costa Mediterránea andaluza

RESUMEN. El objetivo general de este artículo es presentar los principales resultados metodológicos de la evaluación de los riesgos de inundación permanente asociados con el aumento del nivel medio del mar según diferentes escenarios y modelos de cambio climático (IPCC, 2013 y Jevrejeva *et al*., 2012), centrándose en la evaluación de la peligrosidad, la exposición y la vulnerabilidad física de las áreas construidas, especialmente las áreas residenciales en la costa mediterránea de Andalucía (España). Para el cálculo del riesgo se trató un conjunto de datos de mareógrafos y escenarios climáticos para obtener finalmente los niveles futuros para todo el espectro de probabilidades. En este trabajo se propone un método de análisis espacial del riesgo de inundación asociado a cada escenario de subida del nivel del mar mediante el uso de un DTM de 5 m de resolución espacial. Para la evaluación de la exposición y la vulnerabilidad del área edificada, especialmente para las áreas residenciales, se ha utilizado el conjunto de datos más detallado (Catastro Nacional). El modelado de los datos catastrales originales en un sistema de gestión de bases de datos espaciales y su análisis a través de sentencias SQL han permitido identificar las parcelas catastrales con uso residencial y las variables asociadas (área, número de unidades inmobiliarias residenciales, área construida bajo tierra, etc.), constituyendo la parcela catastral la unidad de referencia espacial para el análisis espacial. La superposición del conjunto de parcelas catastrales y los mapas de riesgo de inundación permitieron identificar la exposición de las parcelas catastrales de uso residencial para cada escenario elegido. Se propone un método para una mejor identificación del número de inmuebles residenciales en cada parcela catastral, ya que este número será utilizado como indicador de la vulnerabilidad física de la parcela catastral. La evaluación del riesgo de inundación se calculó como el producto de las variables anteriores. Para la difusión de los resultados de la evaluación del riesgo de inundación, se desarrolló una aplicación web (geovisor). Utilizando el escenario más pesimista, las parcelas expuestas ascienden a más de 24.000 y se identificaron más de 13.000 parcelas catastrales residenciales expuestas para las que se calcularon sus riesgos, exposición y vulnerabilidad para evaluar finalmente el riesgo de inundación asociado a los niveles futuros del mar.

Key words: SLR inundation hazards, physical vulnerability, residential cadastral parcels, web geoviewer, Mediterranean Andalusian coast.

Palabras clave: Inundación por subida del nivel del mar, vulnerabilidad física, parcelas catastrales residenciales, geovisor, costa mediterránea andaluza.

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1. Introduction

Global sea level has risen since the late 19th century around 12-18 cm. An acceleration in its trend has been detected by tide gauges and altimetry satellites during the recent decades. Trends since 1992 have been measured in about 3.4 mm/year, doubling the maximum threshold of sea level rise (SLR) for the period covering the 20th century. The idea of using SLR as a direct consequence of the climate change has increased scientific consensus in recent years. There is a strong scientific consensus in linking SLR with the climate change caused essentially by anthropogenic emissions of greenhouse gases (Nicholls and Cazenave, 2010; Church *et al.*, 2013).

For the last two decades, several forecast of SLR have been made, showing the upward expectations based on different emission scenarios. Although they involve a wide range of parameters, all of them conclude that SLR shows an inertia that it is very likely that it will continue rising during the 21st and even the 22nd century despite the emission scenario chosen (Titus and Narayanan, 1995; Kopp *et al.*, 2015). Therefore, most of the scientific discussion has been focused on the range of the SLR, which vary not only due to the emission scenarios but also due to the climate change model being used. The most robust models synthetize a vast quantity of data and types of variables, having been led by IPCC models for the last three decades. IPCC´s last reports (2019), despite the scenario chosen, often predict rises of 0.4 to 0.9 m by the year 2100. On the other hand, the so-called semi-empirical models estimate that SLR might reach up to 2 m by the year 2100 (Rahmstorf, 2007; Pfeffer *et al.*, 2008; Rahmstorf, 2010). The difference between both types of models lies on the apparently inadequate modeling of the melting process of Greenland (Gardner *et al.*, 2013; Rignot, *et al.*, 2011; Shepherd and Wingham, 2007).

Nevertheless, any work dealing with the local consequences of a SLR should focus not only in the global processes but also in the importance of the local factors (Zazo Cardeña *et al.*, 2003; Zhang *et al.*, 2011; Sayol and Marcos, 2018), which might amplify the local rise trends (due to local subsidence or due to the compaction of sediments) or decrease them, sometimes even inversing them (Johansson *et al.*, 2014).

Different methods have been developed for assessing vulnerability of different coastal systems to climate change impacts. However, one of the common challenges of measuring vulnerability is that vulnerability is temporally dynamic and context specific, because exposure, sensitivity and adaptive capacity vary by type, by stimulus and are place and system specific (Smith and Wandel, 2006).

At this point, it is important to make the distinction between the concepts of flooding, linked to occasional extreme events related essentially to the state of the atmosphere, and inundation which is the occupation of the emerged surface by high tide waters. This second concept is the one in which this work is focused. There are two main types of approaches for evaluating the possible damage caused by the risk of SLR. The first type lies on the calculation of relative indicators of vulnerability, based on the characterization of coastal sectors by means of different variables that indicate the exposure and the value of each analyzed section. It is a very common approach that allows an easy identification of the most vulnerable places (Ojeda *et al.*, 2009; Fraile-Jurado *et al.,* 2019)

The second approach consists on the application of natural risk analysis, in which risk is understood as the probability that a territory (including the society that inhabits it) is affected by natural episodes of extraordinary range. Therefore, the risk is considered as the result of the product of hazard, exposure and vulnerability. The hazard can be defined as the probability of occurrence of a specific adverse event, and it is often provided in terms of values ranging between 0 and 1. The exposure is the probability that a surface element is affected by an adverse event and for the purpose of this paper it can be considered as the hazard mapping. The vulnerability comprises the characteristics and circumstances of a community or system that make them susceptible to the damaging effects of a threat, depending both on their value and also on their resilience.

This approach allows the development of very precise spatial analysis using Digital Elevation Models (DEM) as for instance the work of Gesch (2018). However, the definition of this conceptual framework is complex and allows many interpretations for permanent inundation processes. The hazard is usually valued by means of a single value that represents a permanent flood level, which is linked to the mean value of occurrence according to the statistical model by which the inundation level is calculated. The exposure is very commonly represented by means of dichotomous maps that only distinguish between potentially inundable surfaces and non-inundable surfaces. Therefore, often the probability threshold that distinguishes both surfaces is that of $p > 0.5$. However, some authors (Purvis *et al.*, 2008, Fraile-Jurado *et al.,* 2017) have stated that there are much more open approaches that allow the inclusion of a greater spectrum of probabilities, integrating complete statistical models. Finally, the vulnerability presents the greatest conceptual and methodological dispersion of the aforementioned three, since an enormous variety of approaches have been identified, taking into account elements as different as the economy, the population, the value of the exposed elements, and the resilience (Tascón-González *et al.*, 2020). Here, the residential physical vulnerability of cadastral parcels was used, mainly due to the detailed scale of the National Cadastre, in line with recent works (Jongman *et al.*, 2014; Perez-Morales *et al.*, 2016). Thus, it makes more sense to use the risk terminology of an element to sea level rise, that element being the population, housing or infrastructure, since the complete vulnerability of the entire society and environment in a given territory has not been included in any work on floods caused by rising sea levels.

2. Study area and objectives

The general objective of this article is to present the main methodological results of the assessment of the inundation risks associated with the rise in the mean sea level for different scenarios of climatic change (IPCC, 2013; Jevrejeva *et al.*, 2012), focusing on the assessment of the hazard, exposure and vulnerability of the built areas, especially the residential areas along the Mediterranean coast of Andalusia (Spain). This methodology has been developed in the framework of various Research Projects funded by the Andalusian regional government (see "acknowledgements"). Andalusia region has an exposed coastline of 917 km long, which is divided into two clearly distinct coastal areas (Fig. 1). The Atlantic coast, approximately 300 km long and the Mediterranean coast (just over 600 km long) that constitutes the study area for this work. The Mediterranean coast of Andalusia includes the provinces of Málaga, Granada and Almería, as well as part of the coast of Cádiz and it is characterized by a microtidal regime with short-fetch waves. This is a morphostructural coast controlled by Baetic System, with an inland abrupt and steeply sloped relief with a narrow coastal platform. The result is a heterogeneous coastal fringe with cliff headlands and pocket beaches, medium to large beaches associated with riverine sediments and deltas, as well as lagoons associated with former spits and beach barrier sediments. A large number of coastal infrastructures has also played an important role on coastal dynamic processes (Manno, *et al*., 2016). Intensive agriculture and tourism are ones of the main economic activities. The tourism accounts for 13,1% of the regional GDP (Junta de Andalucía, 2016) on the regional economy, being an important driver in the Mediterranean coast (Costa del Sol).

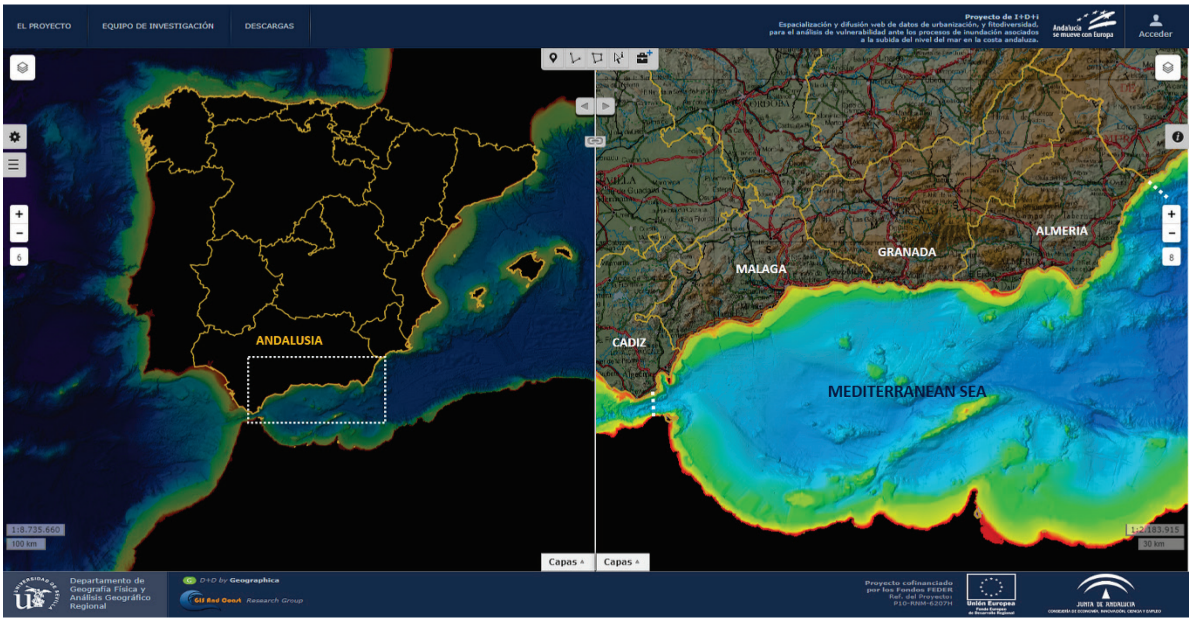


Figure 1. Study area. The Mediterranean coast of Andalusia (600 km long) includes all the coastline of the provinces of Málaga, Granada and Almería, as well as part of the one of Cádiz. Image extracted from the web client (geo-viewer) developed in the project.

For the correct interpretation of this article, it is necessary to emphasize that it focuses exclusively on the risks of permanent flooding (inundation), not including extreme events (flooding) that add to the previous ones those related to storms, waves extremes, surges, or tsunamis. In this sense, the following specific objectives are identified:

1. Sea level rise inundation hazard assessment. Calculating the probability that an inundation event of a particular intensity will occur over an extended period of time. Data from tide gauges and from 4 climatic change scenarios will be used. Unlike many publications that select a probability threshold to identify the exposed lands (generally > 50%), in this case the entire range of

probabilities will be calculated, in order to evaluate the differences between both methodological approaches.

2. Inundation hazards mapping. To spatialize the calculated hazard sea levels on the tide gauges and scenarios, a DTM of 5 meters spatial resolution was used (National Geographic Institute). We are aware of the low precision and accuracy of this DTM, so the results should be interpreted with caution and more as an "indicator" of potential areas where priority should be given and detailed studies with more accurate altimetry data (LIDAR) will be required.

3. Exposure and Physical Vulnerability assessment of residential areas. The calculation is made by the combination of inundation hazard maps with the most detailed information published periodically in the Spanish state (National Cadastre) for constructed areas. National Cadastre uses 1: 500 or 1: 1000 scales for urban areas (cadastral parcel files -CAT format). The methodological proposal is based on modeling of the original information in a spatial database. Therefore, and given the guarantee of periodic publication, the use of defined SQL statements would allow an almost automatic update of future data.

4. Risk assessment for residential areas. Once the hazard, exposure and vulnerability have been calculated and mapped, the risk calculation is methodologically simple, since it is simply a matter of obtaining the product of the three variables.

5. The development of a Web application (geoviewer), which makes use of interoperable OGC web services, in order to provide scientists and stakeholders with a web tool to access and visualize the project results.

3. Data and methods

3.1. Inundation hazards assessment and mapping

3.1.1. Mean sea level inundation hazard assessment

The goal of inundation hazard assessment is to understand the probability that an inundation event of a particular intensity will occur over an extended period of time. Data from tide gauges and from 4 climatic change models/scenarios will be used. Particularly, data from SLR expectations in the Andalusian tide gauges by the end of the 21st century (Fraile-Jurado and Fernández Díaz, 2016) were used for this part of the study. They were calculated by means of the integration of registered SLR trends and four different climatic model/scenarios. Three of them were made by the IPCC (Gregory, 2013) and another one can be considered as a semi-empirical model (Jevrejeva *et al.*, 2012) ("model of Jevrejeva" hereafter) (Table 1), all of them widely discussed (Meyssignac and Cazenave, 2012; Williams, 2013).

Table 1. Mean and standard deviation parameters of the SLR scenarios and models.

Model	Scenario	Mean SLR	Standard Deviation
IPCC (2013)	RCP2.6	0.40 m	0.091 m
IPCC (2013)	RCP6.0	0.47 m	0.097 m
IPCC (2013)	RCP8.5	0.63 m	0.115 m
Jevrejeva *et al*. (2012)	-	0.84 m	0.12 m

As stated by Fraile-Jurado *et al*. (2019), the first step in this phase consists of calculating the maximum possible inundation levels considering three variables:

- SLR expected locally in each tide gauge (Fraile-Jurado and Fernández Díaz, 2016).
- The vertical difference between the topographic zero and the local mean sea level.
- The local height of the high tide for a tide coefficient of 0.7. The last term was included because it allows to add an extra height to the inundation level. This allows to avoid possible errors of the DTM, which often seem to lose accuracy in altitudes near mean sea level. Moreover, the high tide level is a common indicator to estimate flooding and inundation exposure.

The first variable was calculated with data from the tides gauges located in the Andalusian coast, integrating this information into the global models of SLR. This step allows to make subsequent estimations of the SLR for any given probability value (Table 2). The second variable consists of the observed differences between the local mean sea level and the national vertical reference (topographic zero) of topographic maps. Although in the study area it is not very relevant, ranging between 0.12 m in the Strait of Gibraltar and close to 0 values in the eastern coast, in other areas it has proved to be a variable which might be even larger than the future SLR (Fraile-Jurado *et al.*, 2014). There is a similar situation for the third variable, since the tidal range shows small values (ranging from 0.5 in the Strait of Gibraltar to 0.3 m in Almería) and small spatial variability.

Table 2. Expected SLR (m) in the tide gauge of Malaga (first variable) for different probability thresholds, models and scenarios.

Model	Scenario	99%	95%	75%	50%	25%	10%	5%	1%
IPCC (2013)	RCP2.6	0.23	0.29	0.38	0.44	0.50	0.56	0.59	0.65
IPCC (2013)	RCP6.0	0.28	0.35	0.45	0.51	0.57	0.63	0.67	0.74
IPCC (2013)	RCP8.5	0.40	0.48	0.59	0.67	0.75	0.82	0.86	0.94
Jevrejeva *et al*. (2012)	-	0.60	0.68	0.80	0.88	0.96	1.03	1.08	1.16

3.1.2. Inundation Hazards Mapping

The results obtained in the previous step would allow to estimate the value of the local inundation level by the end of the 21st century in a single tide gauge considering the aforementioned three variables, with a SLR probability value of P> 0.5 for each of the four selected scenarios of change in sea level. However, this method is based on calculating the full spectrum of probabilities, so the next step in the process described by Fraile-Jurado *et al*. (2019) consists of the mapping and estimation of the full probability values of permanent inundation for each of the DTM cells of the study area, according to the four considered models/scenarios.

The baseline data used was a Digital Terrain Model (DTM) which covers the totality of the Spanish surface (Instituto Geográfico Nacional, 2013). It was made as part of the first coverage of the National Plan of Aerial Orthophotography (PNOA), and it was downloaded from the CNIG download Center in 2014. The precision and accuracy of the original LIDAR flight used for its elaboration was of 0.5 m for LIDAR points density and a vertical accuracy (RMSz) of 0.2-0.4 m. However, the final estimated vertical accuracy for the MDT downloaded file, at 5 meters spatial resolution (MDT05), was ≥0.5 m. Currently there are new versions of this LIDAR MDT with improved precision and accuracy. In this sense, the proposed methodology could be directly used with the original LIDAR cloud or new versions of higher quality MDT, but the extension of the study area and the treatments required prior to its use, made this option unfeasible in the context of the project, carried out with the technology and data available in the period 2011-2016.

Previous treatment was carried out on downloaded DTM to eliminate the presence of holes and other types of endorheic areas by filling the surface using the ArcGIS 10 "fill" command. This type of analysis allows better operation of the bathtub-type models and guarantees the hydrologic connectivity to sea water level. A second modification consisted in subtracting from the DTM the interpolated surface integrated by the tree variables (average local SRL level + differences to topographic zero level + 0.7 coefficient high tide level) obtained in the previous step (Fraile Jurado and Ojeda Zújar 2012).

The second stage therefore consisted on inundation hazard mapping. To do so, the calculation of the probability of permanent inundation from an accumulated normal statistical model was performed, based on the parameters of normality and standard deviation obtained for each of the four selected models/scenarios (Table 1). Therefore, the value of each cell of the DTM was transformed by means of the following equation (Piña-Monarrez, 2015) which describes an accumulated normal curve (Fig. 2):

$$p(x) = \frac{1}{2}[1 + \mathrm{erf}(\frac{x-\mu}{\sigma\sqrt{2}})]$$

where *p(x)* is the probability of inundation for a given height above mean sea level; x is the height of a cell above mean sea level; μ is the future mean inundation height under the defined inundation conditions; σ is the standard deviation in IPCC scenarios (2013) and Jevrejeva (2012).

As a result, an inundation probability was obtained for each cell and for each of the four models/scenarios analyzed analyzed (Fig. 3). Given that the model is an asymptotic statistical model, it was necessary to limit the value of the upper limit of the results to the average plus three standard deviations. However, this calculation was not necessary for the lower limit since the current inundated area by the high tide was also calculated by means of a bathtub model.

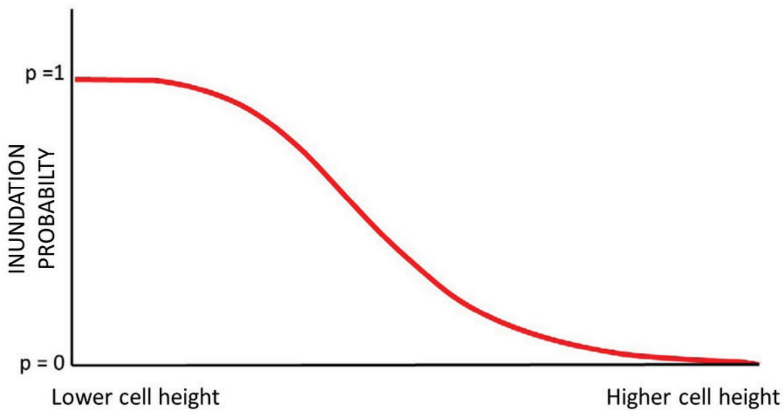


Figure 2. Applied accumulative statistical model of the normal distribution, in which the highest cells get lower probability of inundation and the lower cells get higher probability of inundation.

Figure 3. Four geographically synchronized views in the web client (geo-viewer) developed in the Project (Guadiaro river mouth –Cádiz-): examples of hazards mapping for the scenarios and models selected (RCP 2.6, RCP 4.5 y RCP 8.5 from IPCC 2013 and Jevrejeva 2012).

3.2. Exposure and physical vulnerability assessment of residential cadastral parcels

As stated before, the goal of vulnerability assessment is to understand how a system will be affected by an inundation event. Examples of possible systems could include physical structures such as houses or bridges that could be damaged or destroyed, a business or service whose supply chain could face interruption, or a community that could suffer fatalities, property losses, and negative health impacts in the aftermath of a flood. Therefore, there are different types of vulnerability, but this paper focuses mainly on physical vulnerability -meaning the vulnerability of the built environment to suffer inundation due to mean sea level rise-, and especially along residential cadastral parcels.

3.2.1. Data source: The Spanish National Cadastre

The Spanish Cadastre is an administrative record of properties with a fiscal origin, created as a data bank to be accessed both by Public Administrations (national, regional, local) and citizens. As an inventory of real estate, it contains physical information (surfaces, location, use, shape, boundaries, cartographic representation, crops and forest use, type and quality of constructions, etc.), legal information (identification of holders or owners: name, national identification number, address, etc.) and economic information (cadastral values of land and buildings, valuation criteria).

The download of public data could be done using a digital certificate through the Electronic Office of the Cadastre, on the website of the General Directorate of Cadastre. (http://www.catastro.meh.es/). On the website the information is available for each municipality individually, and both the alphanumeric data (CAT format) and the geometric data (shape format) are linked to the rustic and urban areas.

The alphanumeric data is provided in a flat text file with alphanumeric content of 1,000 characters per line, delimited by a fixed width (CAT format). These data contain, for each real estate, information related to each farm, constructive unit, construction, real estate, distribution of common elements and cultivation register, as the case may be, in addition to the head and tail registers of the file. For the transfer of flat text data to PostreSQL/PostGIS Database Management System, a Python application has been built that allows the selection, structuring and modeling of data in tables automatically. The result of the process of modeling is reflected in the Figure 4 that contains the tables and their cardinal relationships.

3.2.2. Exposure calculation of cadastral parcels for different scenarios

As shown in the Figure 4, the geometric data was provided in shape format (parcels, subparcels, administrative limits, etc.) and among the 3 alphanumeric tables used in this work (cadastral parcels –table 11–, constructions –table 14– and real state units –table 15) it is only possible to establish a spatial relationship with the shape parcels. Therefore, the cadastral parcels will be the reference spatial unit (geo-referenced and scaled to 1:500 or 1:1000 in urban areas and 1:5000 or 1:2000 in rural areas) for the analysis of exposure and vulnerability assessment.

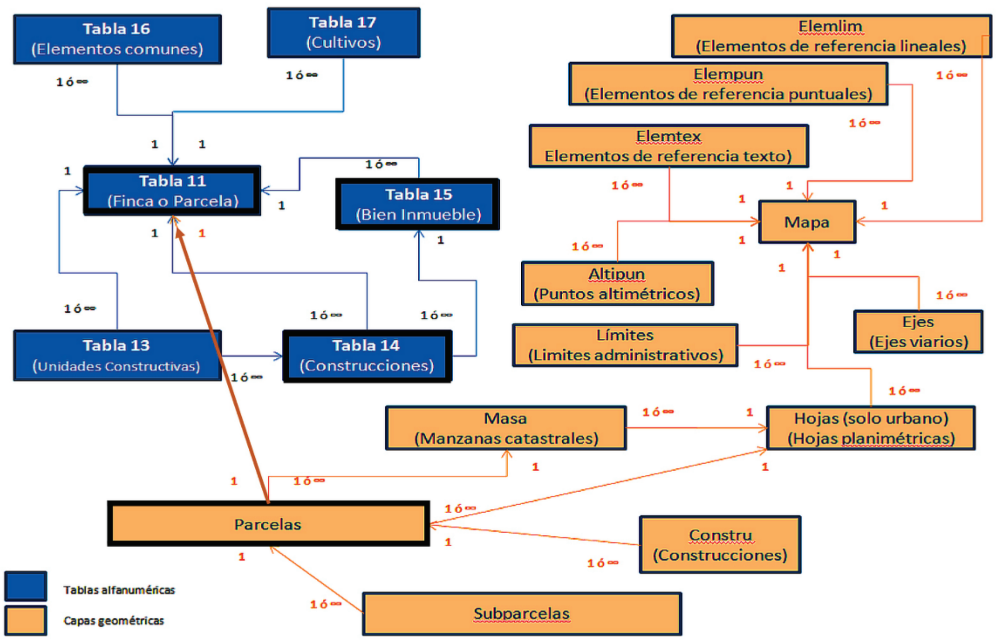


*Figure 4. Database model for the Spanish National Cadastre. The only 3 tables used in this work are: table 11: cadastral parcel (*finca o parcela*); table 14 constructions (*construcciones*) which records the construction units associated with different possible uses; table 15: real estate units (*inmuebles*). Only the table 11 has an alphanumeric relation (parcel register identifier) with the attribute table of geometric layer parcelas –cadastral parcels–(shapefile). In blue the alphanumeric tables are represented whereas yellow represent the geometric shapefiles.*

Methodologically, the calculation of the exposure for each of the cadastral parcels has been carried out with the software ArcGis 10.3 software, using a set of tools available in Spatial Analyst toolbox. The use of raster analysis tools allows to extract for each of the parcels (polygons) the number of pixels present in each of the raster layers (hazard maps) associated with the probability of inundation hazards for each of the models/scenarios selected in this work, as well as to calculate various statistics (average, variety, STD, etc.) that were incorporated into the attribute table of the shape (see Fig. 5).

On the other hand, from the alphanumeric data in table 11 two relevant variables for the final calculation of risk were extracted:

- Dominant use of the cadastral parcels, which is the majority use of all its components (real estate units).
- Total constructed area in m^2, making the sum of all the space built on all the floors (above and below ground) of the buildings or facilities within each cadastral parcel. In turn, two more variables are also provided:
    - o the constructed area above ground in m^2.
    - o the constructed area below ground in m^2.

Finally, all the variables (probability statistics hazards, dominant use, and constructed areas -total, above and below ground-) were incorporated to the attribute table of the shape parcels.

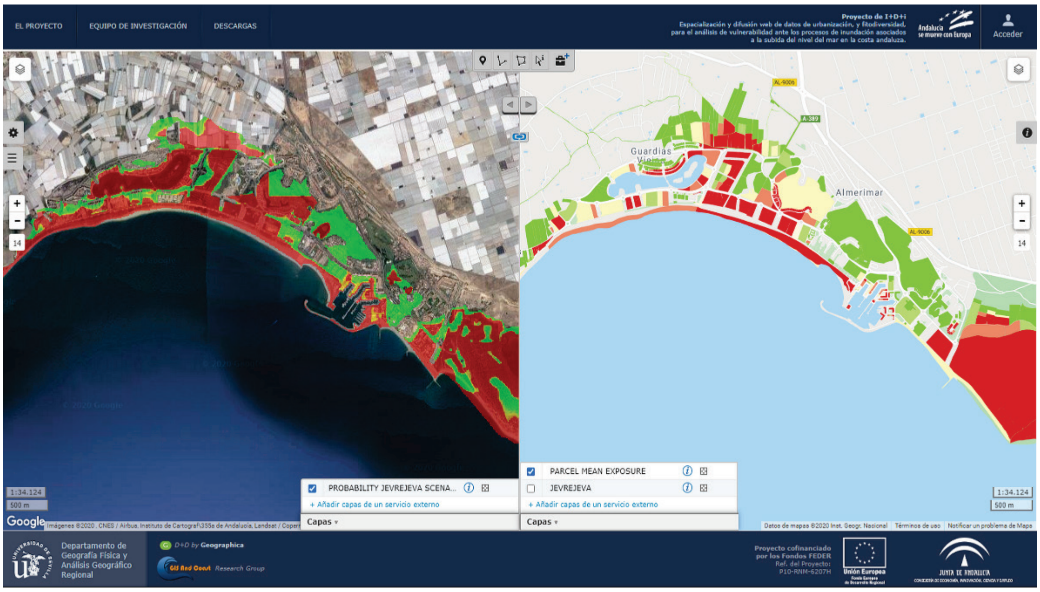


Figure 5. Two geographically synchronized views in the web client (geo-viewer) developed in the Project (western sector of the Almería coast): the entire range of inundation probabilities associated with the Jevrejeva model/scenario (left view) and the average probability associated with the cadastral parcels (right view).

3.2.3. Calculation of physical vulnerability of cadastral residential parcels

For residential physical vulnerability calculation of the cadastral parcels, different SQL statements have been used to extract from table 15 (real state units –*inmuebles*) and table 14 (*construcciones* –constructions units) the number of real state units –*inmuebles*– that they have a residential use (tables were shown on Figure 4). Given the impossibility of extracting their economic value (a variable not accessible in the Cadastre –CAT format– for the general public), the number of residential real estate units have been used as an "indicator" of physical vulnerability for residential cadastral parcels. Thus, two variables have been used for its calculation:

- Number of real estate units –*inmuebles*– (table 15). Each entity in this table has a "main use", among which we have selected those that have a residential use
- Number of residential constructions units (table 14). Each entity in this table has a "destination", among which we have selected those that are of residential use. Since the cardinality relationships between table 14 and table 15 are many to one, with this variable we were finally able of calculating the number of the real estate units (*inmuebles*) where at least one construction unit is intended for residential use.

This second variable increases the number of real state units of residential use (see results) and using the cardinality relationships shown in Figure 4, it is possible to associate its value to the cadastral parcels (table 11). To this regard, the variable chosen to assess the residential physical vulnerability was the "number of real estate units (*inmuebles*) per cadastral parcel that includes at least one construction unit with a residential destination".

Finally, these variables were incorporated to the attribute table of the cadastral parcels shape, along with the rest of the variables previously calculated for the probability of inundation hazards and exposure (Fig. 6).

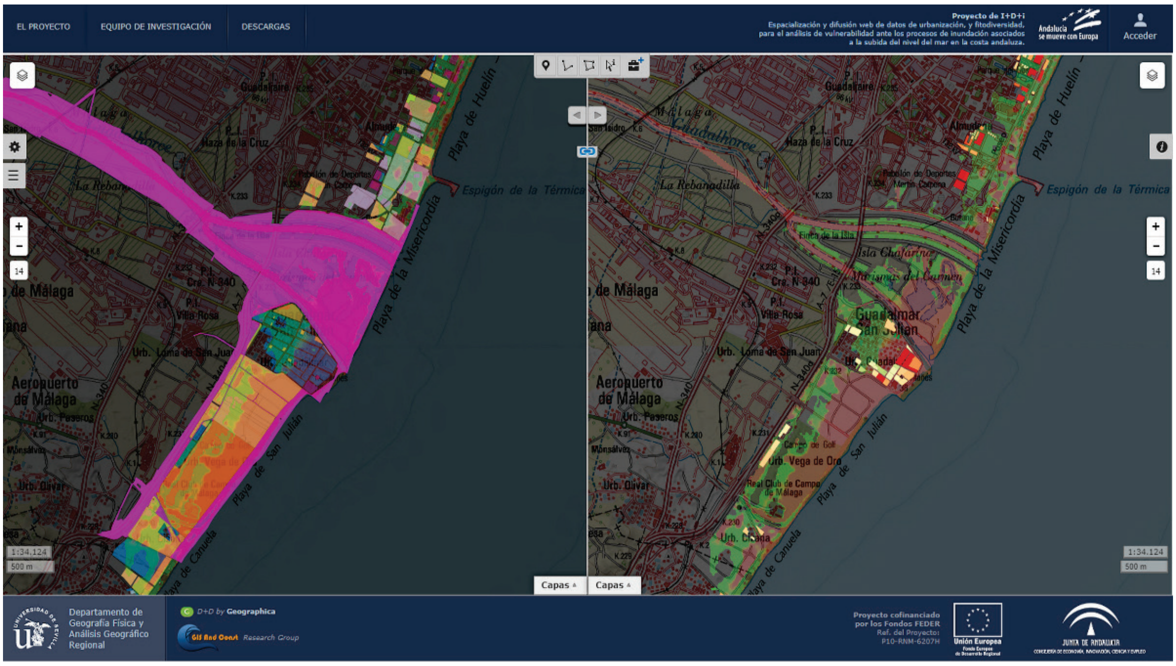


*Figure 6. Two geographically synchronized views in the web client (geo-viewer) developed in the Project (Guadalfeo delta river –Málaga coast–): Cadastral parcels according to their dominant use exposed to Jevrejeva model/scenario (left view) and residential cadastral parcels classified according to the number of real estate units (*inmuebles*) per cadastral parcel that includes at least one construction unit with residential destination, variable finally used for the residential physical vulnerability assessment (right view).*

3.3. Risk assessment for residential cadastral parcels

Once the inundation hazard, exposure and physical vulnerability assessment have been completed, it is relatively simple to arrive at an estimate of inundation risk, since it is simply a matter of obtaining the product of the three variables. Methodologically it is as easy as working with the different variables already included within the attribute table of the cadastral parcel shape: the average probability of the pixels included in each exposed parcels to each of the selected models/scenarios "multiplies by" *the* number of real estate units (*inmuebles*) that include at least one construction unit with a residential destination, used as a "dimensionless indicator" for the residential risk assessment (Fig. 7).

Figure 7. Two geographically synchronized views in the web client (geoviewer) developed in the Project (Almanzora delta river -Almería coast–): Cadastral parcels according to their residential physical vulnerability –number of residential real estate units per parcels– exposed to Jevrejeva model/scenario (left view) and residential cadastral parcels according to their risk, once physical vulnerability is multiplied by the average probability of inundation hazard (right view).

3.4. Web application (Geoviewer)

Finally, a geoviewer, a web application, which makes use of interoperable OGC web services, was the option selected for accessing and visualizing the huge amount of spatial data produced in this work. The development of this tools aims to provide scientist and stakeholders a web tool to understand, interpret and respond to mean sea level inundation risk that would threaten coastal regions in order to prevent or mitigate the possible environmental, social or economic loss. Geoviewer's functionalities (variety of cartographic representations, multiple scale visualization, access to thematic information related to coastal hazards and vulnerability assessment, etc.) are being boosted by the new potential of the spatial databases and web mapping services and moreover, by the new possibilities on client side (HTML5, Javascript libraries, WebGL, etc.).

The developed visualization system (web application) makes use, on the server side, of PostgreSQL v. 9.6.0 and its spatial extension PostGIS v. 2.3 for data warehouse. The map server software used to create the OGC interoperable services (WMS, WMTS and WFS) which feed the geoviewer was Geoserver v. 2.8.1. The geoviewer (client side) has been developed over Leaflet, an open source Javascript library for displaying geographic data in browsers. Besides Leaflet, a set of Javascript open libraries were used to add new functionalities to the geoviewer, allowing users the access to external data.

The visualization system covers the whole coast of Andalusia (Álvarez-Francoso *et al*. 2020) and the deployment in the back-end has been made very flexible by the use of an Operating-system-level virtualization software (Docker). Thus, it could be easily reproduced in any other coastal region due its high flexibility, which has been made possible by the use of virtualization, open source software and standard interoperable services.

4. Results

The scale of detail used for the calculations and assessment of all the components of the risk of mean sea level rise inundation over the built up areas, as well as the extension of the study area (600 km long), made the use of synthetic cartography complex and many times unfeasible. These were the main reasons that justify the development of a web application for results dissemination, constituting in itself one of the main results of this work. Although there is a vast amount of results accessible through the web application (geoviewer) tool (see most of the figures presented here), only the most relevant results resulting from the calculation of the most pessimistic model/scenario (Jevrejeva, 2012) are presented here.

4.1. Cadastral parcels exposure according to the type of land use

Table 3 shows the results related to the exposure of all cadastral parcels in the study area to future sea levels for Jevrejeva scenario, taking into account the type of land use that is dominant among all those present in the cadastral parcel (extracted from table 11 –parcels– shown in Fig. 4).

Table 3. Main figures derived from the cadastral parcels exposed to all the spectrum of probabilities from Jerjereva model/scenario, according their dominant use.

Code use	Parcels dominant use	Nº cadastral parcels	Area of parcels (m^2)	Total constructed area (m^2)	Total constructed area below ground (m^2)	Average probability (Jevjereva)
A	Warehouse-parking	710	1,532,377	2,972,527	744,501	24.79
B	Agrarian warehouse	4	181	183	0	25.39
C	Commercial	403	664,499	757,668	25,581	23.08
E	Cultural	77	366,679	189,148	1,423	18.63
G	Leisure and hostelries	412	1,844,548	1,759,519	156,956	22.91
I	Industrial	806	5,366,519	2,326,962	55,259	20.76
J	Industrial agrarian	21	11,971	4,989	78	26.34
K	Sports	282	17,267,104	14,120,788	21,515	23.78
M	Urbanization and gardening	2,917	43,015,500	251,806	3,268	27.48
O	Offices	79	325,268	115,050	3,051	27.98
P	Singular building	25	202,263	187,378	13,824	24.31
R	Religious	21	20,755	11,629	483	26.66
T	Shows	8	8,897	4,748	380	24.10
V	Residential	12,761	12,671,728	9,364,238	1,478,130	21.12
Y	Health and charities	33	188,700	88,283	7,287	15.88
Z	Agrarian	5,524	2,016,365,573	90,541	127	25.82
	TOTAL OR AVERAGE	24,083	2,099,852,562	32,245,457	2,511,863	22.06

Results show that in this model/scenario (the most pessimistic one) the total number of exposed cadastral parcels amounts to 24,083 and they occupy a total area of more than 209,985 ha. The land uses with the greatest number of exposed parcels are residential, agrarian and those classified as undergoing urbanization. However, if we look at the exposed area of the cadastral parcels, agrarian use stands out, followed by those undergoing urbanization, sports and residential use. Attending to the total constructed area (both in total and below ground) the order is first for sports use, followed by residential, the latter being the dominant one if we only attend to the area constructed below ground.

However, when using the 50% probability threshold, a criterion that is used in many works and publications (Titus and Narayanan, 1995; Purvis *et al.*, 2008) and assuming a dichotomous classification (inundated-not inundated), the results as shown in Table 4 are somehow different. A decrease can be found in all the variables analyzed (as stated in the methodology), reaching 78% in the number of exposed parcels, 97% in the total area of the exposed parcels, 85% in the total constructed area and 63% in the constructed area below ground.

Table 4. Main figures derived from the cadastral parcels exposed to Jerjereva model/scenario using a threshold in probability (> 50%), according the dominant use.

Code use	Parcels dominant use	Nº cadastral parcels	Area of parcels (m^2)	Total constructed area (m^2)	Total constructed area below ground (m^2)	Average probability (Jevjereva)
A	Warehouse-parking	176	459,366	766,209	192,024	89.15
B	Agrarian warehouse	1	51	51	0	98.57
C	Commercial	93	305,022	383,826	11,120	87.24
E	Cultural	12	37,003	17,045	77	96.52
G	Leisure and hostelries	89	452,142	293,275	9,240	88.42
I	Industrial	155	605,085	355,729	20,294	91.39
J	Industrial agrario	6	7,943	2,949	78	78.16
K	Sports	35	790,472	764,635	187	79.48
M	Urbanization and gardening works, unoccupied land	782	9,632,112	41,242	0	84.19
O	Offices	25	192,643	12,476	0	79.24
P	Singular building	7	118,277	116,143	179	77.71
R	Religious	7	4,430	3,547	0	79.36
T	Shows	2	1,304	1,550	0	93.07
V	Residential	2,689	3,938,489	2,169,639	687,117	88.01
Y	Health and charities	4	7,346	4,471	146	85.02
Z	Agrarian	1,194	50,738,591	10,953	31	85.08
	TOTAL OR AVERAGE	5,277	67,290,274	4,943,740	920,493	86.29

4.2. Exposure and physical vulnerability of residential parcels (synthesis at provincial level)

When focusing exclusively on the cadastral parcels that contain some real estate or construction units for residential use, the results are shown in Table 5, also using the exposure derived from the Jevrejeva model/scenario and synthesized at the provincial level.

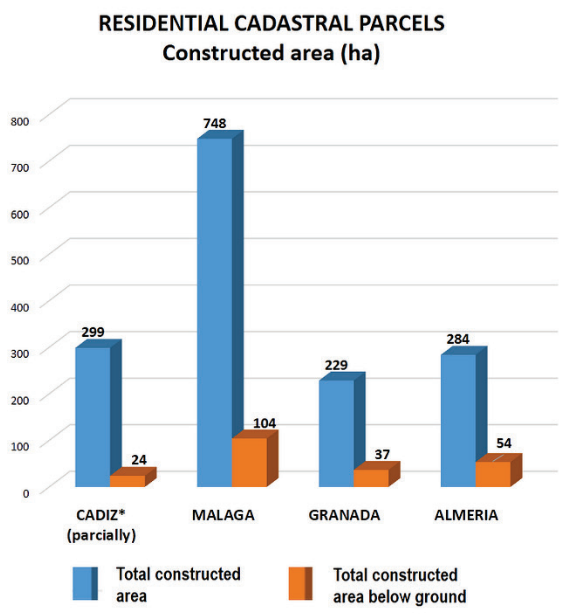
The first relevant finding is the total number of cadastral parcels for residential use that rises to 13,656 for the study area. This number represents 57% of the total of exposed cadastral parcels (including all uses), but scarcely represents 1.5% of the total surface –area of exposed parcels- they occupy (explainable by the wide extension of parcels for agricultural, sports or urbanization use). However, they represent 48% of the total constructed area (counting any floor, above or below ground), increasing to 87% if only the below ground constructed area is considered.

Table 5. Main figures derived exclusively from cadastral parcels exposed to Jerjereva model/scenario containing some real estate or construction units for residential use, synthesized at the provincial level.

Provinces	Nº cadastral parcels	Area of exposed parcels (m^2)	Total constructed area (m^2)	Total constructed area below ground (m^2)	Nº of real estate units (*)	Nº of real estate units (**)	Average probability (Jevjereva)
CÁDIZ (partially)	4,186	9,243,711	2,987,858	240,370	19,379	19,480	16.78
MÁLAGA	3,403	10,011,406	7,478,903	1,041,976	27,198	27,416	8.75
GRANADA	2,929	1,628,659	2,287,094	367,669	20,330	20,356	48.16
ALMERÍA	3,138	8,754,772	2,839,035	536,138	22,397	22,568	15.76
TOTAL OR AVERAGE	13,656	29,638,548	15,592,890	2,186,153	89,304	89,820	22.36

*"*inmuebles*" with main use residential –table 15–
**at least one construction unit –table 14– with residential use

Focusing on the values at provincial level, the number of cadastral parcels for residential use presents similar values, highlighting Cádiz with 4186 (despite only part of the province is included in the study area), followed by Málaga, Almeria and Granada. However, in relation to the area occupied by the cadastral parcels, Málaga (1001 ha) occupies the first place, followed by Cádiz and Almería and, at a great distance, Granada (162 ha). In relation to the constructed area (Fig. 8 –left graph–) also Málaga stands out widely (748 ha), almost with the same area as the rest of the other 3 provinces as a whole, followed by Cádiz and Almería with values close to 300 hectares and finally Granada with 229 hectares.



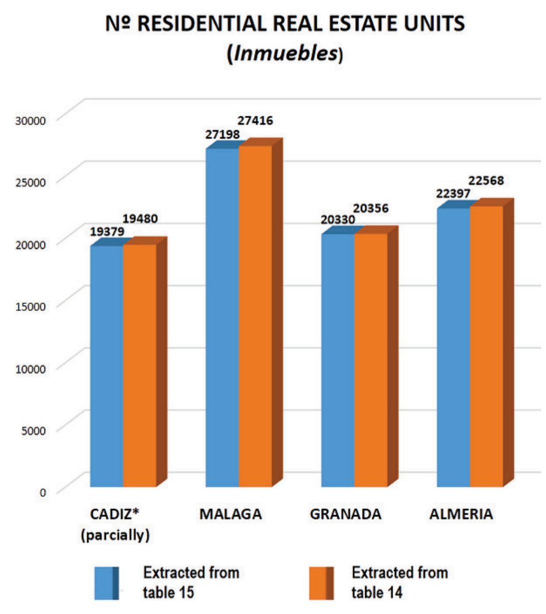


Figure 8. Constructed area in residential parcels (left graph) and number of residential real estate units – inmuebles*– as extracted from table 15 or extracted from table 14 (right graph), exposed to Jevrejeva scenario.*

As stated in the methodology, the number of residential properties (residential real estate units) is the indicator selected to assess the physical vulnerability of the residential areas, in the absence of an economic estimate (not accessible to the general public in CAT format from the National Cadastre).

Two variables were used to calculate the number of residential real estate units, one derived from table 15 (main use) and the other calculated from table 14 (constructions) with which were identified the real estate units where, at least, one "construction" had as its "destination" the residential use. As can be seen in Figure 8 (right graph), they present similar values, although the second variable (extracted from table 14) allows to identify a greater number of real estate units –*inmuebles*- for residential use. Therefore, this variable (*number of real estate units where at least 1 construction has the residential use as destination*) has been used, as an indicator, to calculate the physical vulnerability of the residential parcels. Figure 8 (right graph) clearly shows how Málaga is the province with the highest figures, followed by Almería and finally Cádiz and Granada with similar values. Finally, (see Table 4) in relation to the average probability of inundation of the residential cadastral parcels exposed to this scenario, the parcels of the province of Granada stand out widely with average values of 48%, followed by those located in the provinces of Cádiz (17%), Almeria (16%) and, finally, Málaga with the lowest average probability values (8.5%).

4.3. Risk assessment for residential cadastral parcels

Calculated the inundation hazards, exposure and physical vulnerability assessment of the residential cadastral parcels of the study area from a potential rise in mean sea level according to the models/scenarios chosen in this work, the calculation of risk (risk assessment) in each one (Table 6) has been done by multiplying all these variables that had been incorporated into the attribute table of the shape parcels. As for the previous results, the Jevrejeva model/scenario was chosen for cartography purposes since, by affecting a larger number of parcels, the cartographic representations are more understandable.

Table 6. Main figures derived exclusively from cadastral parcels exposed to Jevrejeva containing some real estate or construction units of residential use for the 4 scenarios selected.

Climatic Scenarios	Nº cadastral parcels	Area of exposed parcels (m^2)	Total constructed area (m^2)	Total constructed area below ground (m^2)	Nº of real estate units (*)	Nº of real estate units (**)	Average probability	Average risk value (dimensionless indicator)
JEVJEREVA	13,656	29,638,548	15,592,890	2,186,153	89,304	89,820	22.36	1.43
RCP85	9,020	25,797,738	11,741,096	1,756,071	61,163	61,289	14.72	0.86
RCP45	4,778	23,253,016	8,916,188	1,389,625	40,245	40,419	19.03	1.18
RCP26	3,767	22,483,409	8,089,685	1,264,487	35,007	35,144	21.45	1.38

*"*inmuebles*" with main use residential –table 15–
**at least one construction unit –table 14– with residential use

The values of the final calculation of inundation residential parcels under risk, in the absence of an economic valuation for residential real estate units, are expressed as a dimensionless indicator that has been classified with percentiles to collect a similar number of parcels in each class. This approach facilitates mapping and interpretation of results and is well suited for dimensionless indicators of this type.

Figure 9 shows –top map–, at municipalities level, the average municipality values of probability hazard and physical vulnerability of the residential cadastral parcels aggregated at each municipal level. The highest inundation probability values from the Jevrejeva model/scenario are located in most of the coastal municipalities of the province of Granada, in the eastern and western extremes of the province of Almeria, in the municipality of Fuengirola in Malaga and in those located north of the Gibraltar Rock in Cadiz. Finally, Figure 9 –bottom map– shows the comprehensive risk assessment with the dimensionless indicator calculated as the product of the previous variables, also as an average value at each municipality.

A synthetic view of the coastal sectors with the greatest final inundation risk from potential mean sea level rise in the Jevrejeva model/scenario, at parcels scale, is shown in Figure 10. In this Figure 25% of all residential parcels were selected, once ordered according to the value of the dimensionless indicator of inundation risk – the highest fourth quartile -, and 5 percentiles were established for mapping them as proportional points. The highest "hot spots" shown by this figure are associated with residential constructed areas which occupied the coastal front of deltas/mouth of rivers (rivers as Almanzora and Adra in Almería, Guadalfeo and Verde in Granada, Vélez and Guadalhorce in Málaga and Guadiaro in Cádiz), as well as with the constructed areas on former sedimentary low lying coastal spits and beach-barrier systems (El Ejido –Almería) or with the sedimentary tombolo of Gibraltar that connects the rocky headland to the mainland in Cadiz. Especial areas also exposed to high risk are those associated with marinas and sportive ports (Benalmádena in Málaga or Sotogrande in Cádiz).

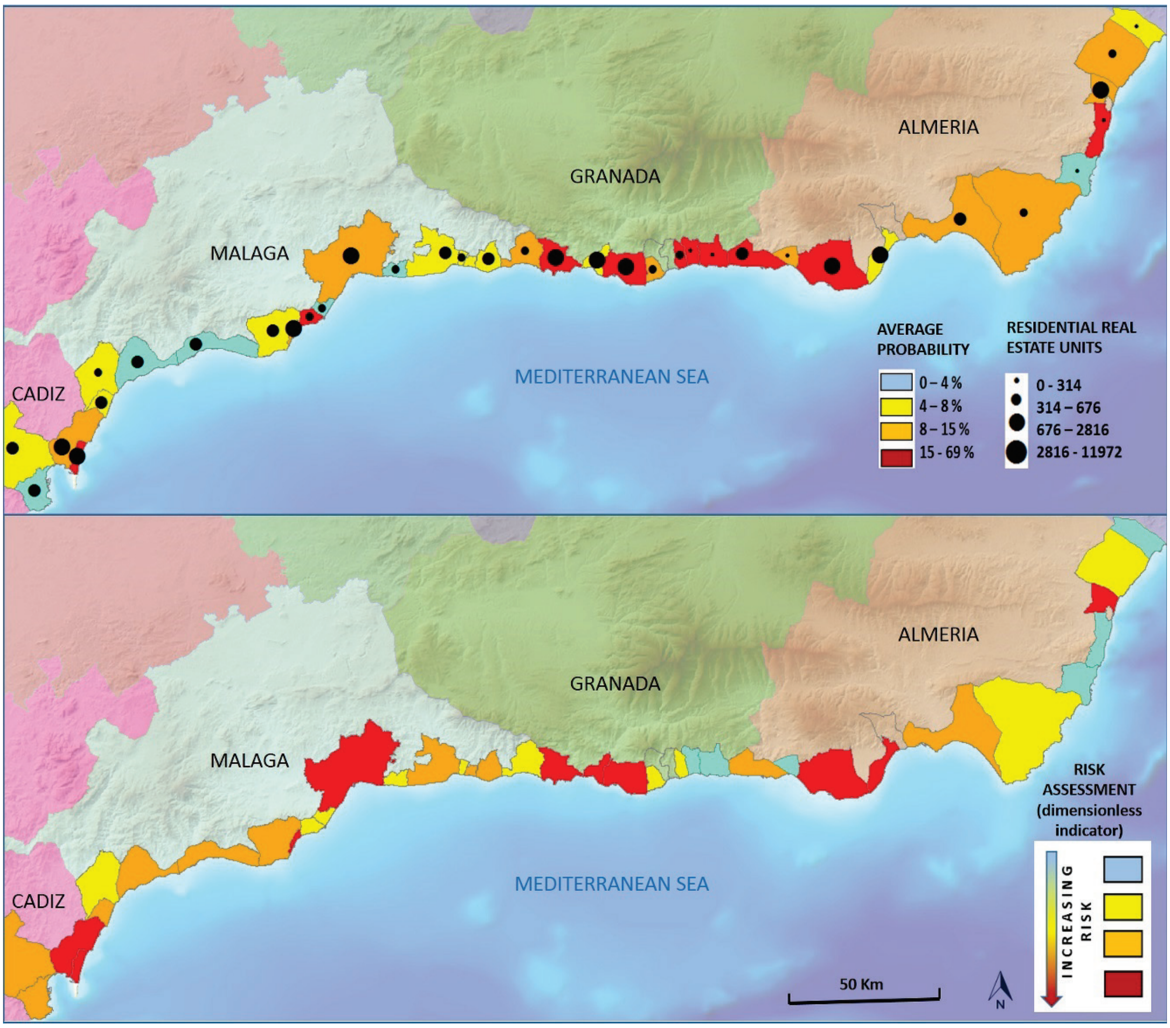


Figure 9. Average municipalities values of probability inundation hazard and residential physical vulnerability –top map– and the average municipalities values of the inundation risk dimensionless indicator –bottom map– of the residential cadastral parcels exposed to Jevrejeva model/scenario

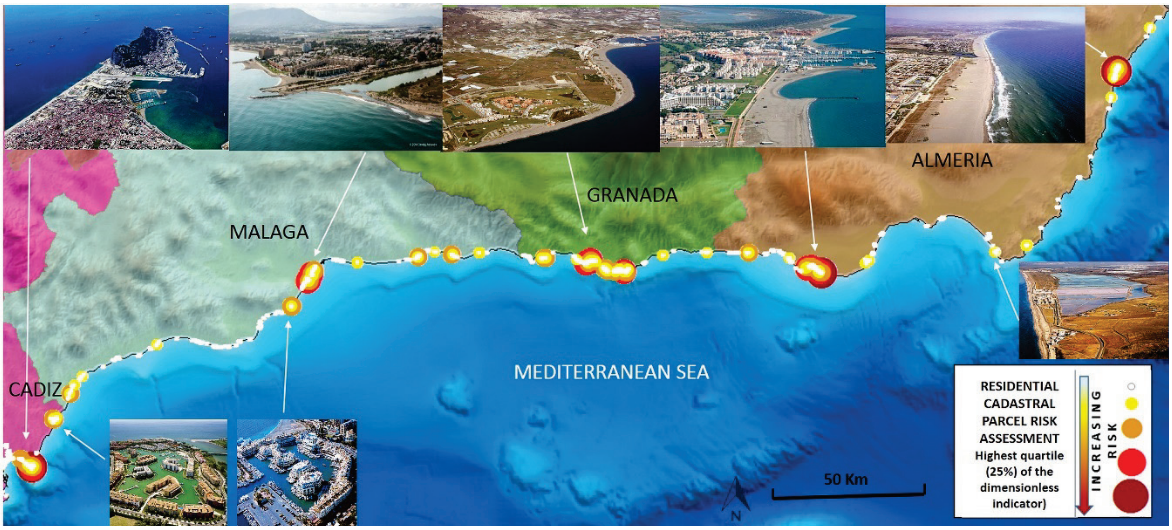


Figure 10. Synthetic map of the residential parcels (mapped as proportional points) with the highest inundation risk values (25% –highest quartile–) from potential mean sea level rise in the Jevrejeva model/scenario.

5. Discussion and conclusions

The proposed methodology for the assessment of hazard, exposure and vulnerability of sea level inundation risks is considered adequate given the objectives set out in this work. In fact, it coincides with the methodology suggested by many international (UNISDR, 2004; IPCC, 2014; Wright, 2015; World Bank, 2016) and national (Kersting, 2016) organizations.

This work confirms that the proposed method of hazard mapping allows a risk analysis of high spatial detail, being mainly dependent on the quality of the input data. It is evident that the input data used can be improved by means of the vertical accuracy and spatial resolution of the DTM (5 m). However, one of the strengths of the proposed method is that allows working with any type of spatial resolution. In fact, the use of DTM based on LIDAR technology with a better spatial resolution would allow risk analysis at building level, even more precise than the one developed here. This phenomenon has been demonstrated in different studies (Fraile-Jurado and Ojeda-Zújar, 2013) in which it was highlighted the high sensitivity of bathtub models to the presence of vertical obstacles in DTM with medium spatial resolution (>5m).

In relation to the methodology and results obtained for the physical vulnerability of residential parcels, the methodological proposal to extract residential real estate units (*inmuebles*) from the National Cadastre (CAT format) represents a great advance. Results have shown that using “constructions units” with residential “destination” is more efficient than the variables frequently used (“main use” of real estate units) and has allowed to identify a greater number of real estate units for residential use. On the other hand, the use of the National Cadastre, at the highest spatial level that allows mapping the assessment results (parcels), represents another major advance over other studies where the reference spatial units for vulnerability assessment are usually administrative areas, basically municipalities. The use of municipalities is in clear imbalance with the level of detail with which the hazards and exposure assessments are currently carried out due to the current availability of high precision DTM (Lidar). The recent dissemination of cadastral data with the new “atom format” (Inspire) seems promising, especially since it especially now integrates the variable number of residential real estate units (dwelling) to smaller spatial units as “building”. This therefore should be further investigated.

Further, modeling and structuring of the original flat text format of National Cadastre (CAT format) in an open source spatial database management system (PostgreSQL/PostGis) has additional advantages. For instance, the guarantee of periodic updating of national cadastre and the use of SQL statements for the extraction of the needed variables, will allow future updates automatically and the reuse of the proposed methodology by other scientists or managers in others coastal areas.

For vulnerability and risk assessment, the economic values of the residential real estate are also critical and this, in the absence of their current availability, has been the reason for the dimensionless indicator used in this article. In this regard, recent research by Fraile *et al*., 2017, applied this method to a small area using a Lidar-based DTM with better planimetric and vertical accuracy and integrating the economic value of buildings. Finally, in relation to the dissemination and access to data and results in projects with this level of spatial detail, especially when new and more detailed data are incorporated (Lidar-data for the hazard exposure or building in atom format for physical vulnerability), the methodological proposal of using an application web (geoviewer) also represents a great advance and, in fact, this type of web tools are becoming irreplaceable for the work of dissemination and management in sea level risk assessment (for instance the works from https://c3e-ar4.ihcantabria.com/ or https://coast.noaa.gov/slr/#/layer/slr).

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THE FLOOD OF OCTOBER 9, 2018 IN THE CITY CENTRE OF SANT LLORENÇ DES CARDASSAR (MALLORCA)

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ABSTRACT. Since the 1940s, the city centre of Sant Llorenç des Cardassar has suffered from several flooding episodes from the several tributaries of ca n'Amer creek. Five lives lost and a significant impact on the population were the result of the most relevant flood in the series that occurred in 2018. In this paper, an analysis of the historical relationship of the village with floods, the answer provided by the administration to those floods, and the geographic setting and the anthropic actions on the land are considered. Using the data collected by direct observation, witnesses, and graphs and fieldwork, a thorough investigation of the volume, flow, direction and levels of water has been developed. This translates into an exhaustive mapping of the event, discriminating the hydraulic behaviour in each of the affected roads and showing the sequential development of the flood. Flooding is a combination of severe stream flows, avulsion processes and angular sections that combine with infraestructures that interfere with the flow direction and prevent its reintegration into the main channel and where the streets become active channels.

La inundación del 9 de octubre del 2018 en el centro de la ciudad de Sant Llorenç des Cardassar (Mallorca)

RESUMEN. El núcleo urbano de Sant Llorenç des Cardassar ha sufrido desde la década de 1940 repetidos episodios de inundación por parte de diferentes afluentes del torrent de ca n'Amer. En 2018 se produjo la riada más importante de la serie que provocó un significativo impacto en la población, con 5 víctimas mortales en la misma. En este artículo se analiza la relación histórica de la localidad con los procesos de inundación, la respuesta a los mismos por parte de la administración y el entorno geográfico natural, y las actuaciones antrópicas sobre el territorio. Se lleva a cabo una investigación detallada de los caudales, flujos, direcciones y niveles, todos ellos basados en la observación directa, los testimonios presenciales y gráficos y el trabajo de campo. Ello se traduce en una cartografia exahustiva del evento discriminando el comportamiento hídrico en cada una de las vías afectadas y mostrando el desarrollo secuencial de la inundación. La inundación es el resultado de la combinación entre caudales incidentes extremadamente importantes, procesos naturales de corte en meandros y tramos angulosos que se combinan con infraestructuras que interfieren el flujo del agua e impiden su reintegración al canal principal. Todo ello en un contexto en dónde las calles actúan como elementos de canalización activos.

Key words: Natural hazards, geography of risk, Mallorca, Sant Llorenç, flash flood, urban floods.

Palabras clave: riesgos naturales, geografía del riesgo, Mallorca, Sant Llorenç, flash flood, inundaciones urbanas.

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1. Introduction

The island of Mallorca shows significantly similar physical and territorial features to the Mediterranean coastline of the Iberian Peninsula. Even considering the limiting factors regarding its insularity and the reduced surface of basins, it is also affected by the same flood pattern described in the flash flood model with equally catastrophic consequences to the nearby continental areas. Those events have been historically recurrent (Grimalt, 1992) although in the first years of the 21st century they were less devastating than in other geographical regions nearby such as Murcia (Romero and Castejón, 2014) or the surrounding European Mediterranean territories (Llasat *et al.*, 2013). Floods in island areas with significant tourist development have also been studied in the Canary Islands (López *et al.,* 2019), with evident parallels with the case of the Balearic Islands. In the absence of gauge data, the post-event study of floods using alternative methods offers good results (Bačová *et al.,* 2018; Macchione *et al.,* 2019).

On October 9th 2018, there was a flood in the oriental coastline of Mallorca which affected the municipalities of Sant Llorenç des Cardassar and Artà, as well as Capdepera, and Manacor, to a lesser extent. The event was severe regarding the volume of flow and the associated destruction caused, in particular to the locality of Sant Llorenç des Cardassar and Son Carrió. There were 13 lives lost, which represents an extraordinary death rate considering that in the period between 1960 and the present time (2020) counts with 25 lives lost in Mallorca as a consequence of floods (Grimalt-Gelabert *et al.,* 2020). Out of the 13 deaths registered in October 2018, five were in the city centre of Sant Llorenç, two of them in their place of residence, and three were dragged in vehicles.

This paper characterises the dynamics and analyses the circumstances of the flood in the city centre of Sant Llorenç.

2. Area of study

2.1. Superficial hydrography of Mallorca

The hydrographic network of Mallorca (Fig. 1) consists of a group of sporadic water flows (referred to as *torrent* and *xaragall*). There are no permanent rivers, except for reduced sections that are permanently fed by agrarian drainage systems.

The network is organised in 4 main watersheds, determined by the orography of the land, with two parallel mountain ranges: Serra de Tramuntana and Serres de Llevant, both close to the occidental and oriental coastline, respectively. The central part of the island is located between them, and it is relatively plain. It shows some minor reliefs which subdivide it into two watersheds that lead into the bays in the south occidental and north oriental limits of the island (Palma and Alcúdia).

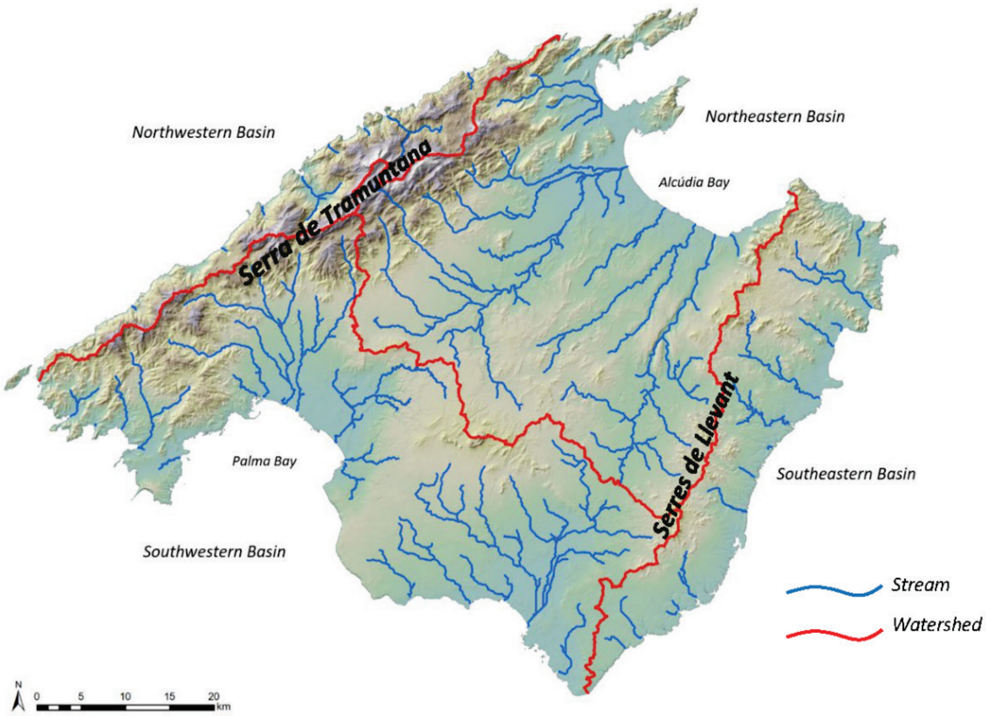

Figure 1. Distribution of the superficial hydrography of Mallorca.

2.2. Torrent de ca n'Amer watershed features

The present paper refers to the water flow of *ca n'Amer*, which is located in the south oriental watershed, formed by a gathering of relatively short tributaries that flow from Serres de Llevant towards the coast. The summits of the mountain range barely reach 500 m above sea level, but given their proximity to the coast, they register a relatively significant slope (approx 12% average in the watershed).

These tributary streams follow a NW-SE layout, being the main ones located in the northern side of the basin. A morphometric analysis of the layouts (Grimalt *et al.,* 1990) makes a difference from the creeks in the northern area (*torrent* de Canyamel, *torrent* de ca n'Amer, and *torrent* de ses Taioles) from the other ones.

From a geomorphological point of view, there are several coastal lagoons in the mouth of the main water flows. The high dynamic activity of these lagoons shows the recurrence of flood episodes of high erosive power (Estrany and Grimalt, 2014; Grimalt *et al.*, 1992).

Torrent de ca n'Amer has a basin of an area of 78.07 km^2, and a perimeter of 53.6 km (Fig. 2). It is formed by the gathering of three main tributaries. Several watershed parameters are the elongation ratio (0.65) and Gravelius index (1.7).

Torrent de ses Planes is the main tributary of the course and originates in Puig d'Alpara, with an altitude of 487 metres above sea level. It drains sa Begura/Infern basin, a valley constituted by marlaceous terrains of low porosity in which erosion has caused a notably dense fluvial layout in a land with hills and thalwegs which favour flow gathering. The valley exits through a canyon (Es Gorg) and then receives the tributary *torrent* de s'Arboçar with very similar density and impermeability features at its headwaters.

The second tributary is *torrent* de sa Blanquera, rising at Puig de Calicant (473 m above sea level), which flows above marl calcareous soils and lays over a silt clayey plain layout with artificial drainage modifications. Both tributaries join in the immediate city centre of Sant Llorenç des Cardassar.

The third tributary, xaragall den Fava, rising at Serra de Pocafarina (349 m above sea level), joins the main course in the surroundings of the city centre of Son Carrió.

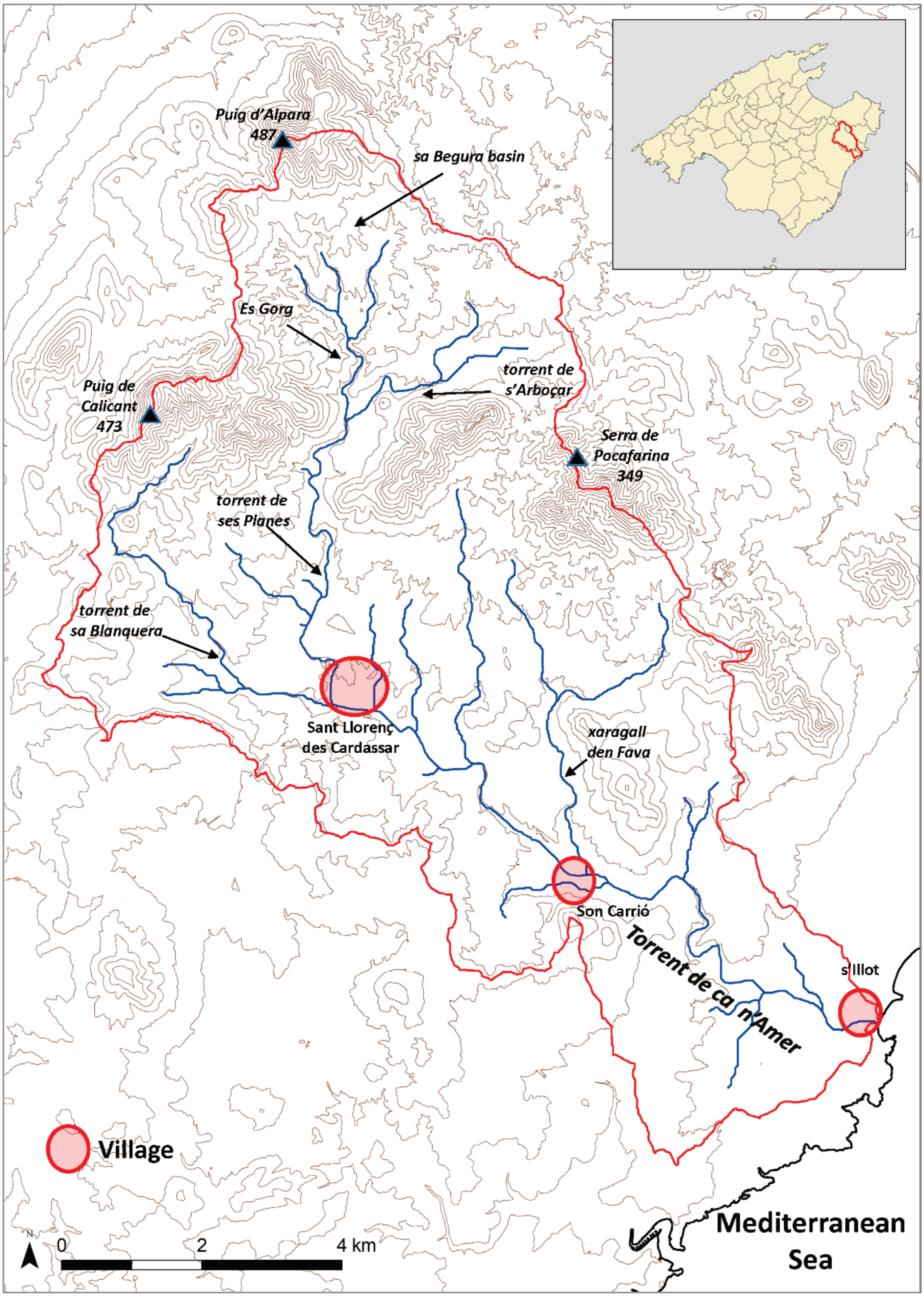

Figure 2. Torrent de ca n'Amer basin.

From a geomorphological perspective, the rising of all three water flows happens at the axial side of Serres de Llevant, where calcareous and marlaceous materials alternate. They then flow at the foothills, an area of hills and open valleys, which presents a range of land permeability. Their course ends crossing the Miocene platform of Sa Marina, which is extremely karsted and permeable and that digs a meandering canyon.

The mouth features a longitudinal coastal lagoon (*Riuet de s'Illot*), which has undergone several relevant modifications: it was drained out in 1973, and the 1989 flood subsequently reformed it. After the flood, the administration restored the wetland with a partially coinciding layout with the original one.

2.3. Torrential rain in the eastern quarter of Mallorca

The east of Mallorca shows the ideal conditions for episodes of heavy rain, in particular in situations of eastern cyclonic advection or Mediterranean depressions, as in the oriental coastline of the Iberian Peninsula.

There were 68 episodes between 1930 and 2010 which exceeded 100 mm in 24 hours (Grimalt and Genovart, 2014). The storms on 4th October 1957 (400 mm registered in Santanyí) and the one on the 6th of September 1989 (over 250mm in es Picot, Manacor) are remarkable regarding the amount of rainfall.

51% of those episodes happened in cyclonic circumstances, with depressions arround the Balearic Islands, and the eastern cyclonic advection were responsible for 22.45% of them. A lower percentage of heavy rainfall occurred in undefined atmospheric situations. Season-wise, 85.2% of the more torrential rainfalls are focused in the second half of the year, from August to December.

2.4. Previous floods in the area of study

Torrent de ca n'Amer has historically suffered from numerous severe floods and associated destruction (Table 1). Floods have been documented since the first decades in the 20th century since the growth of the city centres of Sant Llorenç, Son Carrió, and s'Illot sprawled over the adjoining areas to the course of water and flooding translated into the damage of civilian architecture. In the same period of time, there were certain constructions linked to communication (bridges and embankments) which modified the watercourse. Previous to the past century there are a few documentary sources which detail the problems of surface waters in Sant Llorenç related to the insalubrity of dam waters next to the village, but there is no mention to floods. Table 1 summarises the essential information of episodes of flooding in the basin.

Two of the floods mentioned above reached a remarkable volume of water and caused severe destructive effects. On the 30th September 1959, the rainfall focused on the lower basin of the creek, basically on the tributary Xaragall de na Fava. The flood took down the bridge of Pont de ca n'Amer (10 m high) (Rosselló, 1964). One person died, dragged by a minor tributary of Son Moro.

The flood in 1989 affected the oriental and meridional half of the island, with an overflow of all of the tributaries of *torrent* de ca n'Amer, resulting in the severe destruction in the three inhabited centres of Sant Llorenç. As a result of the draining of the coastal lagoon in the 70s and the subsequent obstruction of the mouth of the creek, the seaside locality of s'Illot faced the most devastating effects of the flood. Son Carrió, at the downstream of Sant Llorenç also registered disastrous consequences.

Table 1. Main episodes of flooding in Sant Llorenç 1940-2020. The degree of severeness varies: anecdotic (*), mild (**), notable (***), severe (****), and catastrophic (*****). (Grimalt, 1992; Grimalt and Rosselló Geli, 2011; Grimalt et al.*, 2019).*

Date	Watercourse	Rainfall (mm)	Degree	Circumstances
02.11.1943	Torrent de ses Planes	276 (Son Crespí Vell)	***	Flood in the city centre of Sant Llorenç.
30.09.1959	Xaragall den Fava	194 (Son Servera)	****	It was restricted to the coastline. It floods Son Carrió. Destroys a bridge (Pont de Ca n'Amer). One life lost, pedestrian dragged by a minor tributary in a rural area.
22.10.1959	Torrent de sa Blanquera	143.5 (Artà)	*	It blocks the road Sant Llorenç-Palma.
12.10.1973	Torrent de ses Planes	88.5 (Son Crespí Vell)	***	Flood in the city centre of Sant Llorenç.
29.03.1974	Torrent de ca n'Amer	143 (es Cabanells)	*	Floodings in rural areas.
03.11.1982	Torrent de ses Planes	103 (es Pou Colomer Vell)	**	Flood in the city centre of Sant Llorenç.
25.10.1985	Xaragall de sa Muntanyeta	63.8 (Son Sard)	**	Flood in the eastern quarter of city centre of Sant Llorenç.
06.09.1989	Whole basin	170 (Can Xesc)	****	Severe effects in Sant Llorenç, Son Carrió and s'Illot. Several bridges and infrastructures collapse. Some vehicles get dragged.
22.11.2007	Torrent de sa Blanquera	77.2 (Son Carrió)	**	Flooding in the city centre of Sant Llorenç. It blocks the road Sant Llorenç-Palma.
09.10.2018	Whole basin	257.0 (Sant Llorenç)	*****	Severe effects in Sant Llorenç, Son Carrió y s'Illot. Several bridges and infrastructures collapse. Numerous vehicles get dragged. Nine lives lost.
20.01.2020	Whole basin	205.6 (Sant Llorenç)	**	It blocks the road towards Palma. Flooding focused on Sant Llorenç and Son Carrió.

2.5. Downtown Sant Llorenç and hydrographic network

Sant Llorenç des Cardassar is the main population centre of the homonymous municipality, with 3,545 inhabitants (2018). The historical development of the village initiated in a long hill (76-82 mamsl). In the southwestern edge of the hill there is a church devoted to Saint Lawrence, after whom the village is named. This raised area served as the origin of the first road layout, as well as several constructions that stretched to the north, following the topography of the area and sprawling laterally.

As a consequence, the origins of the locality were a nucleus located over a piece of raised land, limited by the main course of water in the system, *torrent* de Ses Planes, and with a minor stream of water limiting the north oriental part of the settlement (xaragall de sa Muntanyeta). In the first decades of the 20st century, the building expanded towards the south and the west. It moved towards the foothill next to *torrent* de ses Planes in a lesser elevated topographic level in relation to the hydric course.

Torrent de ses Planes in the urban surroundings of Sant Llorenç flows relatively fitted into a valley of unsymmetrical topography (Fig. 3). In the first pre-urban section, the northern bank is raised, with a small cliff, where the cemetery is located, and that coincides with the occidental edge of the topographic hill from the original urban layout.

Next, the characteristics of the terrain change. The *torrent* has the west bank that coincides with an elevation and the east bank –where the lower part of the town is located- is almost at the same level as the channel.

Finally, after receiving the contributions from the tributary of sa Blanquera, the southern bank of the canal is elevated, while the northern bank, which borders the urban nucleus, is not elevated in relation to the channel.

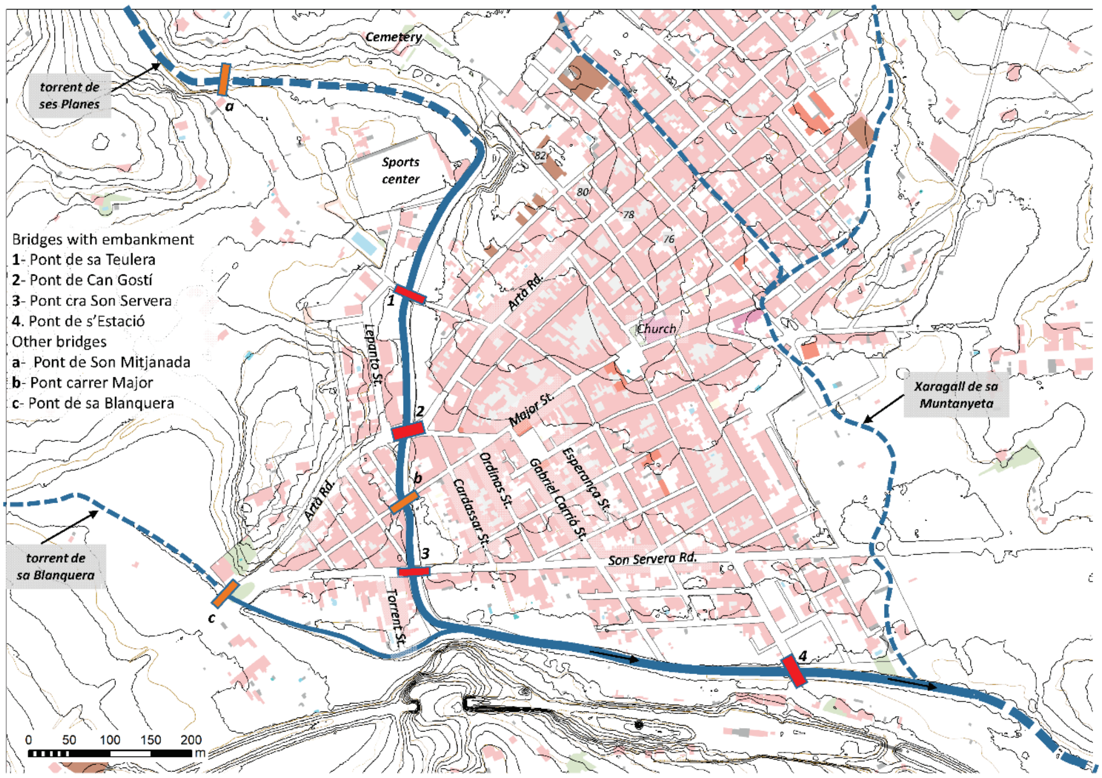

Figure 3. City centre of Sant Llorenç des Cardassar. Topography (contour interval 2 m) and hydrography. Main urban toponyms.

2.6. Alterations of the watercourse of torrent de ses Planes in the city centre of Sant Llorenç des Cardassar

In the second half of the 20th century, the layout of the watercourse through the city centre has undergone several modifications, some of them as a response to floods (Fig. 4).

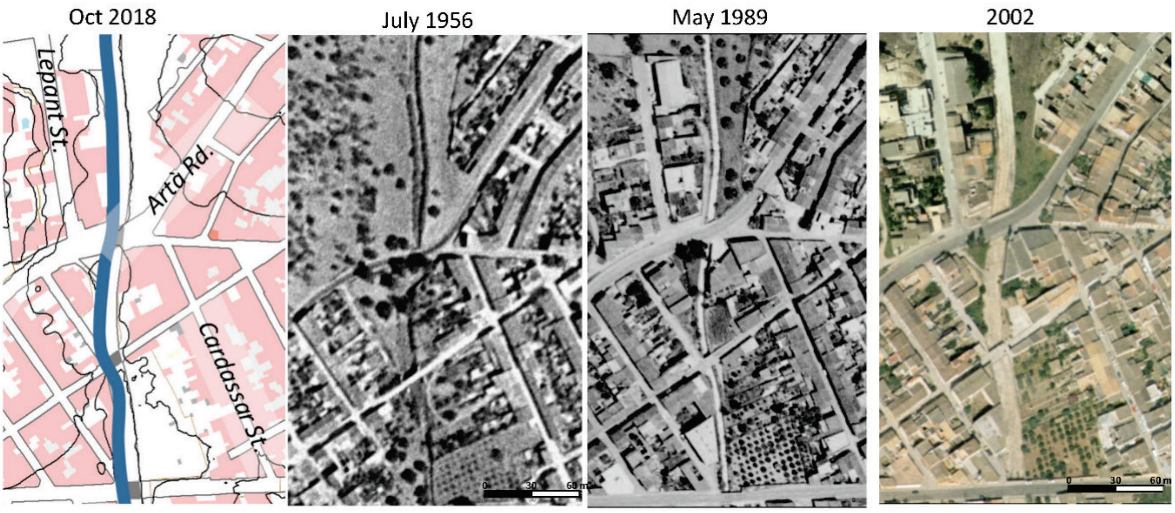

Figure 4. Aerial view of Sant Llorenç, which was already settled in 1956. Between 1970 and 1998, only a few warehouses and buildings were added in the area close to the watercourse, and the streets surrounding Lepant street were built. The watercourse was upgraded from a small canal (1956) to an artificial 4-metres-wide cemented canal in the 70s and 90s. In 1990 it was widened to 12 m, after the flash-flood in 1989.

Until the 70s, the *torrent* did not have any sort of artificial channeling, being back then a stream with the minimum dimension as to allow the scant usual water flow. In the first years of the decade, it was regularised and transformed into a cemented, walled canal but of reduced capacity (4 m width - 1.2 m depth).

The flash-flood of the 12th of October 1973 proved the construction insufficient since the course overflowed in the same flow direction that it would in later events. As a response, there were several upgrading proposals which involved the building of a dam (Grimalt, 1992), which were never executed.

The flash-flood of 1989 wiped out or compromised the integrity of the majority of the existing bridges over the watercourse. Upstream, the estimated water flow calculated with geomorphological methods is 252 m^3/s. The response of the Regional Authorities was to expand the canal to 12 m wide and 2 m deep, with an average slope of 0.008 m/m. The bridges were rebuilt with a rectangular span fitted to the canal measurements.

The remarkable size of the new canal provided the population with a sense of security, even though its capacity (of approximately 140 m^3/s in ideal conditions in the initial section) was below the water flow registered in the flash-flood that had pushed its building. The satisfaction of the population with the new canal was reinforced after a heavy rainfall in 1990 when it proved capable of containing the presumable overflow that would have been registered in the previous circumstances. However, the new water bank did not encourage more building in the immediate surroundings, since the sporting facilities, buildings or warehouses close to the watercourse which were affected by subsequent floods were previous to the widening of the canal.

3. Objectives and methodology

The present paper aims at analysing the flood processes suffered in the city centre of *Sant Llorenç des Cardassar* during the episode of 9th October 2018. Water levels have been found out and mapped, main stream flow lines are established and natural and anthropogenic factors that have caused the phenomenon are investigated.

In the period between October 2018 and April 2019, there has been a direct information gathering, as well as evidence to achieve the set goal. Since there are no official gauging stations in the basin, the investigation has been developed using geomorphologic evidence, along with alternative information sources (Portugués *et al*., 2016; Macchione *et al*., 2019; Segura-Beltran *et al*., 2016). The marks of high water have allowed the estimation of the height of the flood, water flow and flow direction both in the water bank and in the affected urban areas, registered through a systematic check in the field.

These data have been contrasted with graphic documents, photos, and videos, allowing a better estimation of the flow and its features, in addition to the chronology of the event, flow direction, and the speed of the water flow. Interviews with direct witnesses of the event, as well as a compilation of experiences and interviews by Josep Cortès (Cortès, 2019), have also been used to complete and contrast data. Part of the research group were also witnesses of the event, which supplies live data observation on-site.

3.1. Peak discharge estimation

A combination of several methods has been used in order to estimate the peak discharges.

In the urban grid plan, data collected in Grimat *et al.* (2019b) and the technical report (Grimalt *et al.*, 2019a) have been considered. The calculations derive from the usage of Manning and Riggs formula.

The peak discharges in non-urban areas has been calculated establishing a channel cross-section departing from the high-water marks left on vegetation and structures. Following similar methodology as Rico and Benito, 2002 or Grimalt and Rodríguez, 1990. The peak discharge is established with additional information about the slope, hydraulic radius, and water depth, along with the diameter of dragged subspherical boulders.

The measurements have been taken in unhindered locations with no change in the direction of the channel. Fieldwork was done in the two following weeks after the episode, counting with pieces of evidence left by wood debris, which accurately show the reached water levels.

In order to quantify the runoff**,** diverse alternative and complementary methodologies have been used, keeping those used in previous studies (Grimalt and Rodríguez, 1990) in the same area.

The two kinds of empirical formulas are:

- The formulas that determine the peak discharge from the slope of the channel and the cross-section of channel stages: Riggs formula (Riggs, 1976), and Manning (quoted by Dalrymple and Benson, 1989).
- The formula that shows peak flood velocity considering the diameter of water-dragged boulders. With this method, established by Costa (1983), the volume of water is calculated multiplying the speed times the section. To apply the formula, the diameter of the five most voluminous boulders was measured. Only those with a subspherical shape were considered, which is those with a length lower than two-thirds of the biggest longitude.

Riggs formula discharge flow as in:

$$Q = 3.39\ At^{1.39}\ S^{0.32}$$

Where *Q* represents the discharge in m^3/seg, *At* is the cross-sectional area in m^2, and *S* is the slope in m per m. For the present study, slope (applied in both Riggs and Manning formulas) was obtained with a digital elevation model with a spatial resolution of 2 m, generated for this study from Lidar files (density of 0,6 points per meter) from a 2014 flight by Instituto Geográfico Nacional.

Manning equation was used in its initial form:

$$Q = 1/n\ At\ R^{0.66}\ S^{0.5}$$

Where *Q* is discharge in m^3/s, *n* is the roughness coefficient, *At* is the section of the channel in m^2, *R* the hydraulic radius, and *S* slope channel in m per m.

In the measuring areas where there were subspherical boulders, Costa equation was applied in order to calculate peak flood velocity:

$$Vc = 0.18\ Dm^{0.49}$$

In which *Vc* is peak flood velocity according to Costa in m/seg, and *Dm* is the average diameter of dragged subspherical boulders.

The final discharge was established as the average of Riggs and Costa formulas. The flow calculated with Manning equation was used as a referencing element and possible measuring error indicator. If Manning value differed significantly from the other formulas, the point would not be considered.

If the discharge calculated with the Costa method showed a lower value as compared to the other formulas, the value would not be considered, since the anomaly is attributed to the lack of boulders.

3.2. Analysis of the behavior of overflowing water

The analysis of the flood in the urban area was determined by the marks left behind by the water in building façades and street furniture. The flow direction has been established from the visualisation of images, witnesses and material evidence. It must be taken into account that the flow in certain areas was in sections of very low/nonexistent slope.

The data available from the state-owned company SITIBSA, which manages the cartography of the Balearic Islands, has been used to extract cartographic information. In addition to that, the group has generated some digital modelling of terrain using the point file as in Lidar from the 2014 flight by Instituto Geográfico Nacional de España. The information from the 1956, 1973, 1989, 2002, 2015, and 2019 flights, also available from the same source, has also been taken into consideration for the interpretation of orthophotos.

4. Flooding episode on 9th October 2018 in downton Sant Llorenç

4.1. Rainfall on 9th October 2018

The flood on 9th October 2018 was linked to a storming episode of constant regeneration, defined by Doswell et al., (1996) as convective train. The rainfall was particularly heavy upstream of *torrent* de ca n'Amer, affecting some other watercourses in the same basin (*torrent* de Canyamel, *torrent* de ses Talaioles), and Alcudia's basin (*torrent* de na Borges).

The storm was static, favoured by the relief, and fed by a mild eastern flow. It originated in the south of the basin and it moved extremely slowly towards the north. Rainfall reached 200 mm in a wide area (Table 2) that covers from the litoral of Alcudia bay to the north up to Sant Llorenç city centre.

Table 2. Rainfall during the episode. Source: AEMET (*), Meteobaleares (**), Particular (***).

Observatory	Rainfall 9 october 2018 (mm)	Max. rainfall in an hour (mm)	Max. rainfall in 10 min. (mm)
(Torrent de ca n'Amer basin)			
Sant Llorenç (*)	220.0		
Sant Llorenç (**)	257.0	51.6	9.4
Son Garriga (***)	217.0		
Son Carrió (**)	184.4	76.0	17.2
Son Carrió Son Fred (*)	209.5		
(surrounding area)			
Manacor Son Crespí (*)	121.0		
Artà (*)	149.8	56.8	15.4
Son Servera Son Sard	97.2		

The time-intensity is more remarkable than the total rainfall, featuring heavy rains that alternated with light drizzling. The chart from *Son Carrió* observatory (Fig. 5), in lapses of 10 minutes, evidences this alternance.

The flood, as a consequence of prolonged rainfall, rose relatively slowly in level in comparison to the usual timing of flash floods in the oriental watershed of Mallorca. The rising constantly swelled over 15 min (personal observation), which contrasts with the preceding flood in 1989, where the rising reached the maximum flow almost immediately with no previous flow.

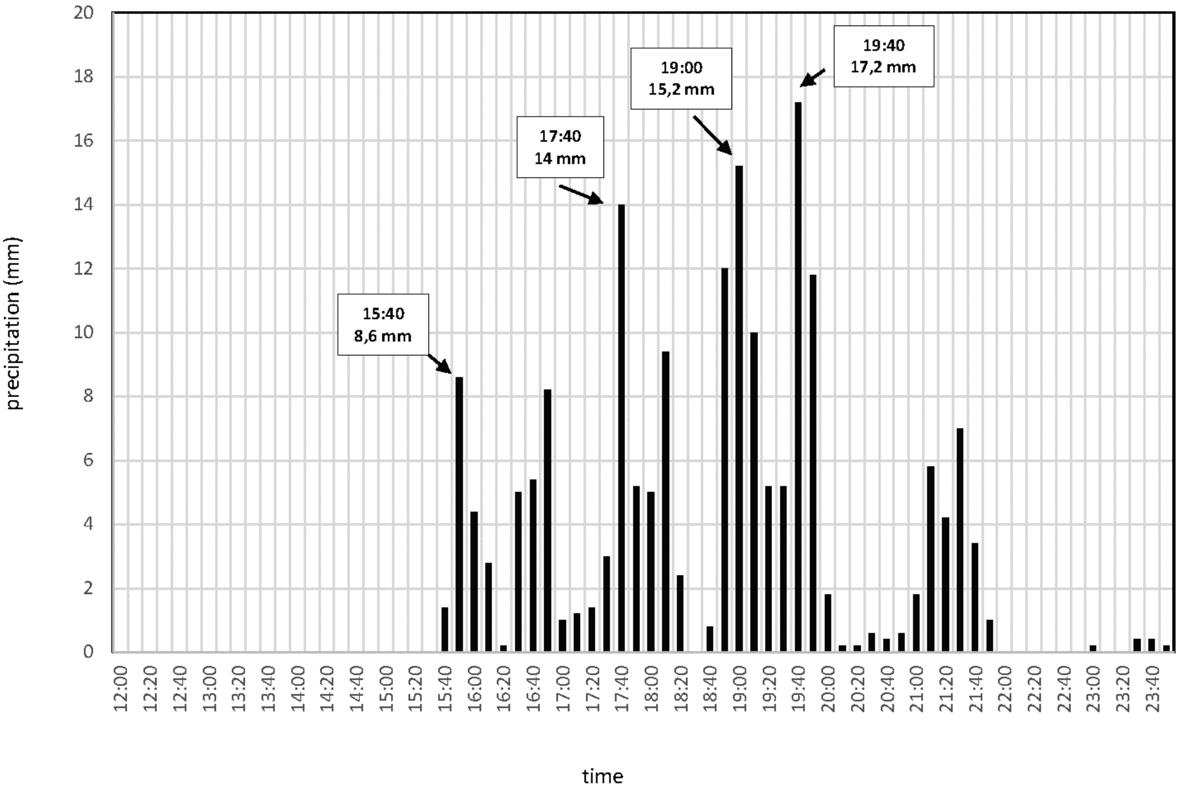

Figure 5. Rain distribution from Son Carrió *observatory. The episode initiated at 15:30 h and lasted until 22:00 h. There are several peaks of intensity, being the one between 18:50-19:50 h the most remarkable one, with 76 mm in an hour span. The peak flood happens this same hour.*

The relatively slow rising allowed, within minutes, for people to find shelter. Even so, for the same reason, some vehicles kept in motion regardless of the increasing water level. The peak, which extended for half an hour, provoked severe material compromise of urban furniture and both personal belongings and commercial goods.

4.2. Flows upstream Sant Llorenç in 2018

An estimation of the peak flow has been made through geomorphologic systems, which allows for an estimated calculation of the magnitude of the event.

In the 1989 flood (Grimalt and Rodríguez, 1990), *torrent* de ses Planes registered a maximum 113 m^3/s (within a 41 m^2 section), which increased after joining the tributary *torrent* de s'Arboçar to 245 m^3/s (80 m^2), being the latter the peak that reached the urban area. In the same locations, the peak in 2018 was significantly higher, with an estimated flow of 426.33 m^3/s and 631.63 m^3/s in respective sections of 71.44 m^2 and 119.54 m^2.

Torrent de ses Planes reached the surroundings of Sant Llorenç (Fig. 6) in a straight line, confined in a valley with no flooding plain, with a section of 122.43 m^2, which translated into a peak of flow close to 750 m^3/s. When it entered the meander upstream of the village, both the section and flow were reduced, redirecting the flow towards sporting facilities. At the moment of reaching the first urban bridge, the peak had been reduced to a section of 115.7 m^2, and flow of 533.6 m^3/s, which represents sensibly lower values.

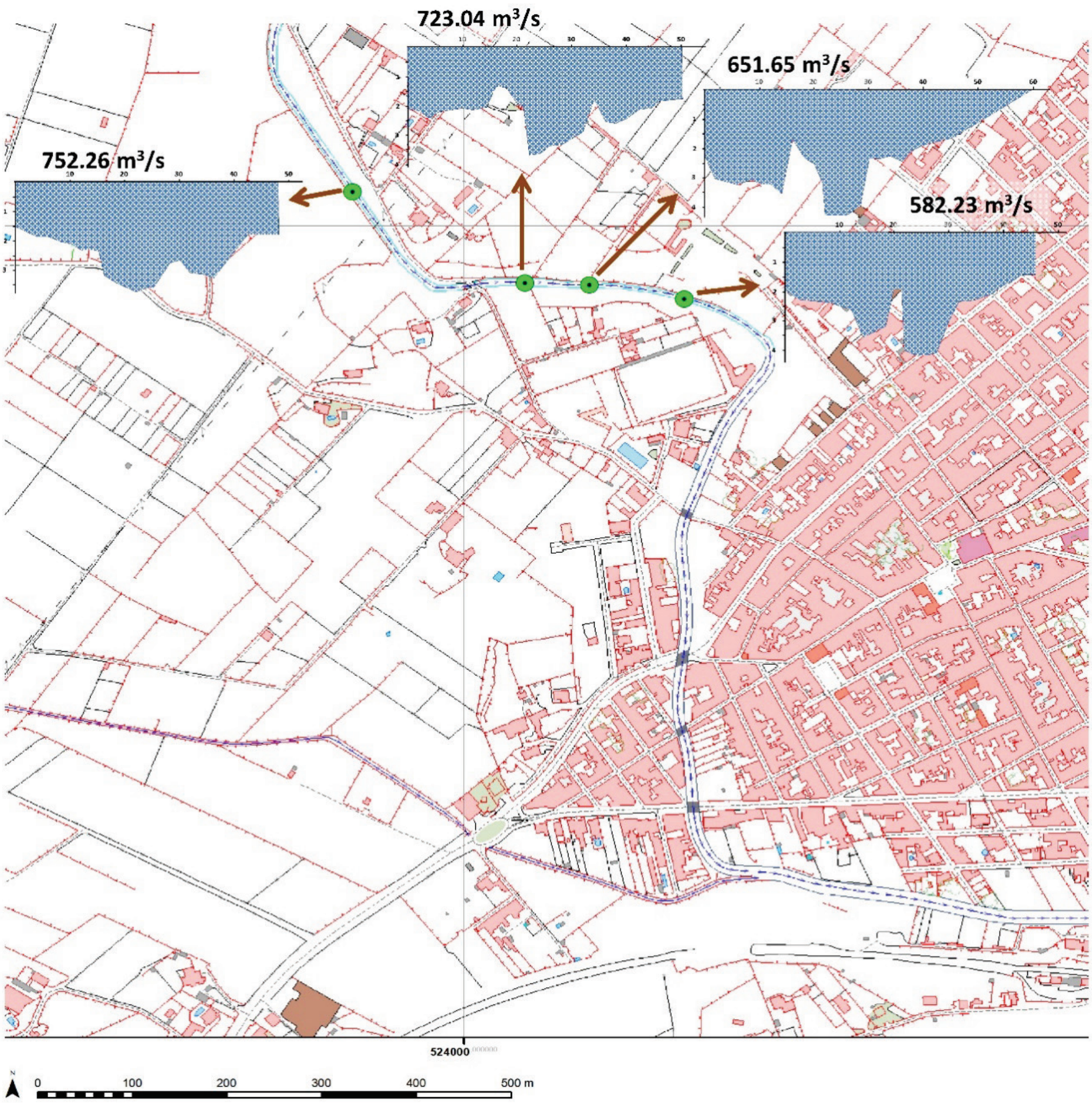

Figure 6. Sections in the area preceding the entrance of torrent de ses Planes to the village.

Regardless of the overflow, the rise exceeded the capacity of the channel built in 1990, as well as the capacity of the first bridge (Pont de Sa Teulera), which decreased as a result of the debris and sediments carried by the water. The loss of capacity of the bridge and the dam effect due to the bridge embankment resulted in an increase of the water level upstream and the diversion of flow into neighbouring streets. It also prevented the flow that had gone through the sporting facilities to reintegrate into the main watercourse.

The resulting flow values could seem extremely high, considering that they are calculated in areas of relatively imprecise lateral limits. However, an unequivocal section of the flood in the road-rail bridge (Fig. 7) downstream from Sant Llorenç, with a span of 100 m^2, shows that it operated to maximum capacity, which supports the estimation of 600 m^3/s.

The flash-flood of October 2018 in *torrent* de Ses Planes was the most relevant documented flood until the present time. *Torrent* de sa Blanquera presented an ordinary raise and it did not overflow the existing channelling. Also it was lower than previous episodes such as the ones in 1989, 2007, or even past events (2020). That is why the analysis is focused on the first watercourse.

Figure 7. Rail-road bridge over torrent de ca n'Amer*, with a total span of 100 m^2. During the flood in 2018 it worked to its limit, being used as flow control point.*

4.3. Urban flood

4.3.1. Sequential development of flooding in the urban area

The development of the flood in the urban area is described based on the cartography of the stages of the process. (Fig. 8, 9, and 10).

The bridge Pont de Can Gostí goes across *torrent* de ses Planes, holding the road to Artà. The span of the bridge was not wide enough to allow the watercourse since the surrounding buildings to both sides prevented the overflowing water from reintegrating to the main watercourse. As a consequence, a remarkable part of the waters flow leaning east towards the city centre. The street that leads towards the east flooded up to 2,85m above the pavement. From that point, following the slopes, the overflowing water entered Cardassar, Ordines, Gabriel Carrió, and Esperança streets, at a high speed (3 to 4 m/s). The perpendicular streets to the previous ones flooded slowly.

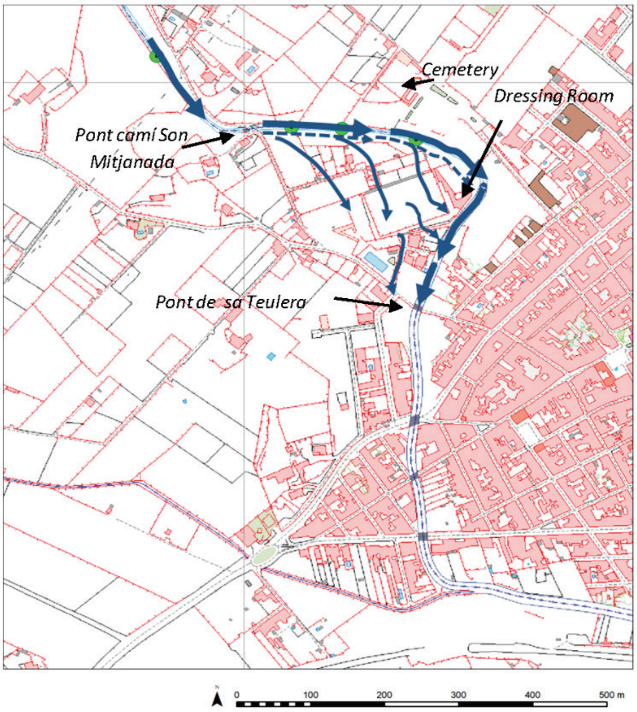

Figure 8: Simplified cartography of the watercourse previous to the urban area. Flood flows in two parallel canals to the changing rooms of the sporting facilities. There are overflowing waters in the whole section leading south, shortcutting the meander. From the northern side, the flood reaches the cliff meeting the cemetery and damaging it partially. Dressing rooms hinder the water flow and provoke an increase in the water level. Downstream towards the football stadium, water is favoured by a small topographic prominence where the pool is and it flows towards the bridge Pont de sa Teulera.

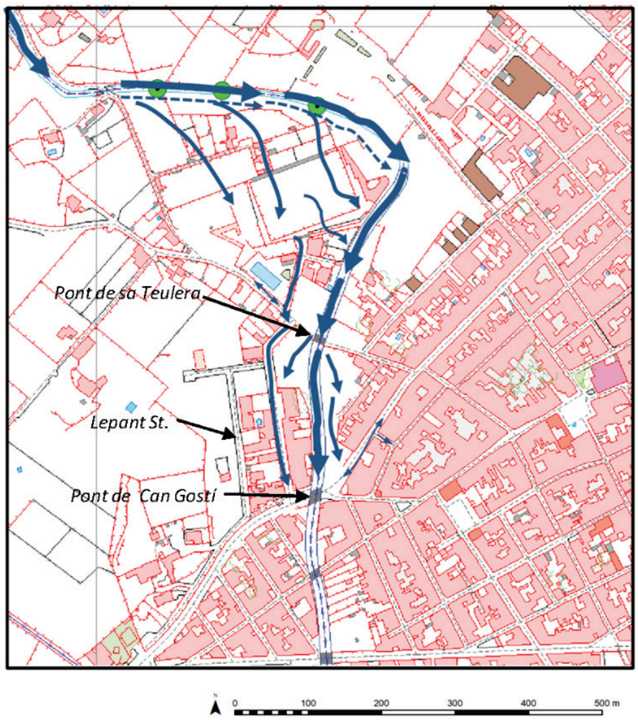

Figure 9. Scheme of overflow from the bridge Pont de Sa Teulera. The flood forks on both banks as a consequence of the dam effect of the bridge and its embankment To the west, it streams down the Lepant st. and reaches levels up to 1.8 m above the pavement. To the east, it floods some gardens and damages the road. Due to the insufficient bridge capacity, it makes the level of water rise up to 2.85m in the surrounding streets.

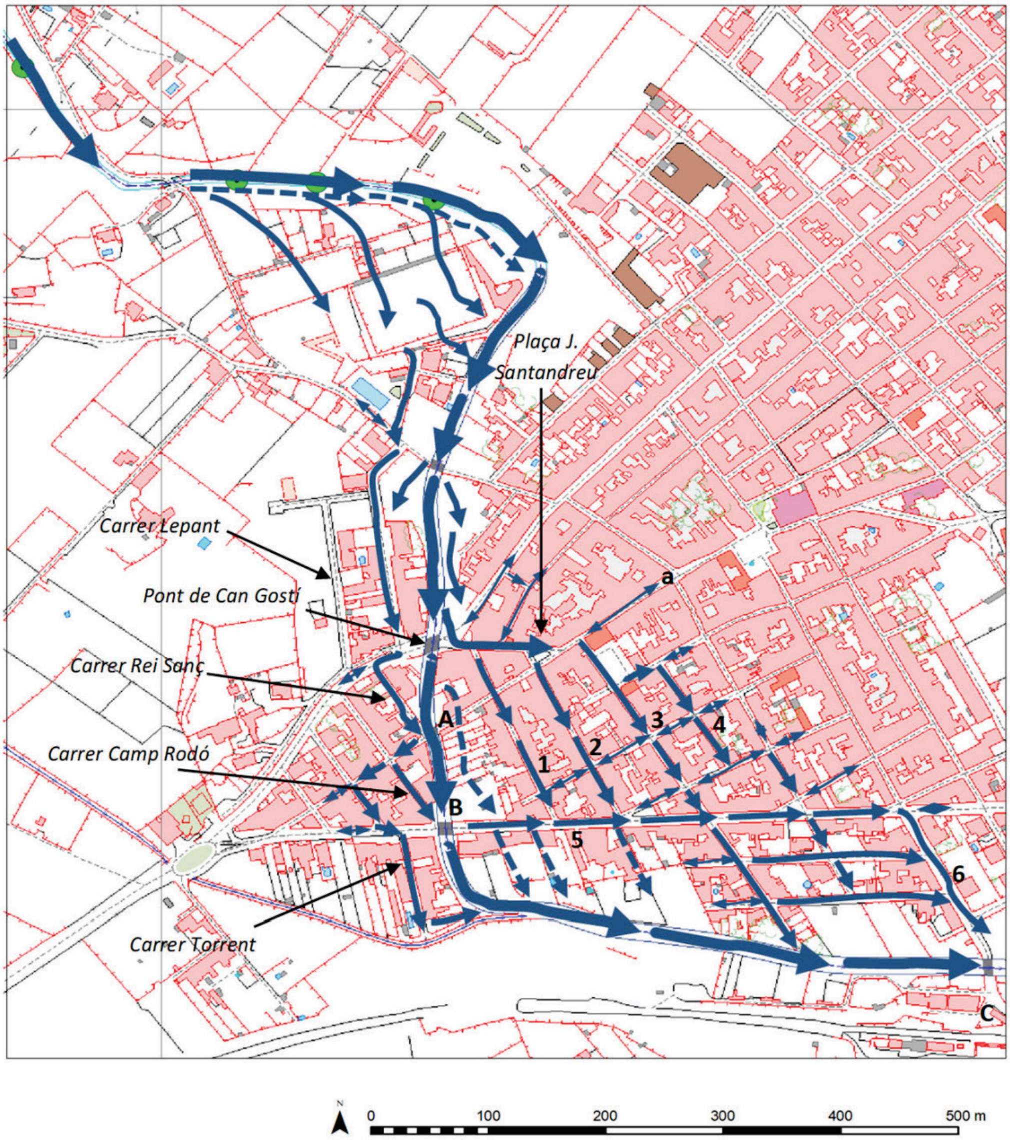

Figure 10. General scheme with flooding lines in the downtown of Sant Llorenç provoked by the dam-effect of the bridge Pont de Can Gostí. The flood to the west went upstream in Major street (a), and flooded Cardassar, Ordines, Gabriel Carrió, and Esperança streets (marked with numbers 1-4). Cardassar and Ordines streets do not lead to the watercourse, but they finish when crossing the road to Son Servera (number 5). The flow of water did not manage to reach the torrent until the end of the streets Gabriel Carrió and Carrer de la Mar (number 6). On the westbound of the torrent, the overflowing waters reached street Lepant and moved on through streets Rei Sanç and Camp Rodó towards the road to Son Servera. Afterwards, they led into torrent de Sa Blanquera. The two bridges of insufficient span in Major street (marked as A), and in the road to Son Servera (marked as B) also hindered the reintegration of overflow water to the main course and contributed to the expansion of the flooded area. Even having an insufficient span, the bridge Pont de s'Estació (marked as C) did not obstruct the watercourse.

4.3.2. Volume of overflow in the main streets

Applying the Manning formula, the volume of water flowing through the main streets has been calculated (Table 3 and Table 4), considering a high roughness rate corresponding to the pavement and the debris dragged by the water flow. Observing the videos, the accuracy of the speeds derived from the application of the formula described has been verified.

Table 3. Water levels, wet section, slope, and volume of water in the west bank of Torrent de ses Planes.

Street	Street width (m)	Water level (m)	Section (m^2)	Wetted perimeter	Hydaulic radius	Slope (m/m)	discharge (m^3/s)
Lepant	9.5	1.8	17.1	13.1	1.305	0.0125	75.98
Rei Sanç	6	2.5	15	11	1.364	0.013	69.96
Torrent	6.5	1.3	8.45	9.1	0.929	0.017	34.97
Camp Rodó	6	1.5	9	9	1	0.035	36.74

Table 4. Water levels, wet section, slope, and volume of water in the east bank of Torrent de ses Planes.

Street	Street width (m)	Water level (m)	Section (m^2)	Wetted perimeter	Hydaulic radius	Slope (m/m)	discharge (m^3/s)
Cardassar	5.5	1.8	17.1	9.2	1.076	0.0086	32.12
Ordines	5.5	2	15	9.5	1.158	0.011	42.36
Gabriel Carrió (N)	7	1.4	8.45	9.8	1	0.014	38.65
Gabriel Carrió (S)	8.5	1.4	9	11.3	1.053	0.014	48.56
Cardassar	5.5	1.8	17.1	9.2	1.076	0.0086	32.12
Ordines	5.5	2	15	9.5	1.158	0.011	42.36

The observed water flows are remarkable, bound to significant speeds, equal or superior to 3 m/s, which explains the capacity of the water to drag urban furniture or vehicles found in the course. Considering these values (Fig. 11), it can be noticed that, from the bridge Pont de Can Gostí, the runoff in the streets on the western bank was 69.9 m^3/s, corresponding to the street Rei Sanç. The runoff in the streets on the easten bank was 121.3 m^3/s (corresponding to the sume of flow of several streets).

It is considered that the urban flow of the flood upstream from the mentioned bridge was of 530 m^3/s. A considerable share (191.2 m^3/s, that is 36.08% of the flood) flowed through the streets and reintegrated to the main channel with a certain difficulty. It redirected in parallel to the road to Son Servera, which is in a higher topographic level than the main watercourse. All the streets parallel to the flow direction became active channels with flows at high velocity since the streets slope was equal to or greater than that of the main channel of the *torrent*.

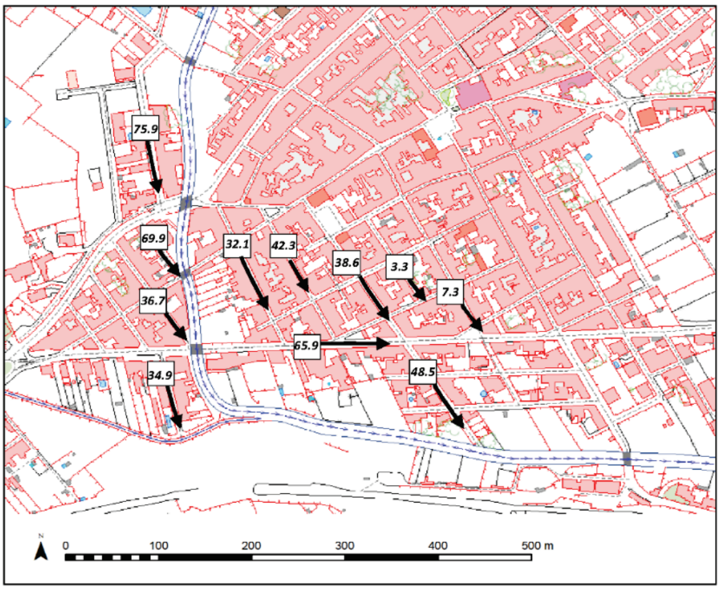

Figure 11. Peak flow in Sant Llorenç des Cardassar (in m^3/s) and flow direction in the main affected streets.

4.3.3. Levels reached by the flood

Through fieldwork, 230 water level heights above the pavement have been listed, as well as a precise limitation of the areas affected by the flood. With this information, the maximum levels of the flood in the urban area have been cartographed (Fig. 12).

There were two areas which reached critical levels:

The first one follows the watercourse, with level of up to 5.5 m upstream the bridge *Pont de Can Gostí*. Water marks over the channel surpassed 3 m at all times. There is an increase/decrease path of the watermark related to the interferences provoked by all the bridges.

The second area which reached critical levels starts in the bridge *Pont de Can Gostí* and it expands to the streets *Cardassar*, *Ordinas*, and *Gabriel Carrió* to join with the road to *Son Servera*, parallel to the main watercourse.

The hindering provoked by vehicles or debris occasionally rose the levels, but it never determined the direction of the flow, which was governed by more relevant factors such as the slope or water level. That is why it has not been considered in the development of cartography.

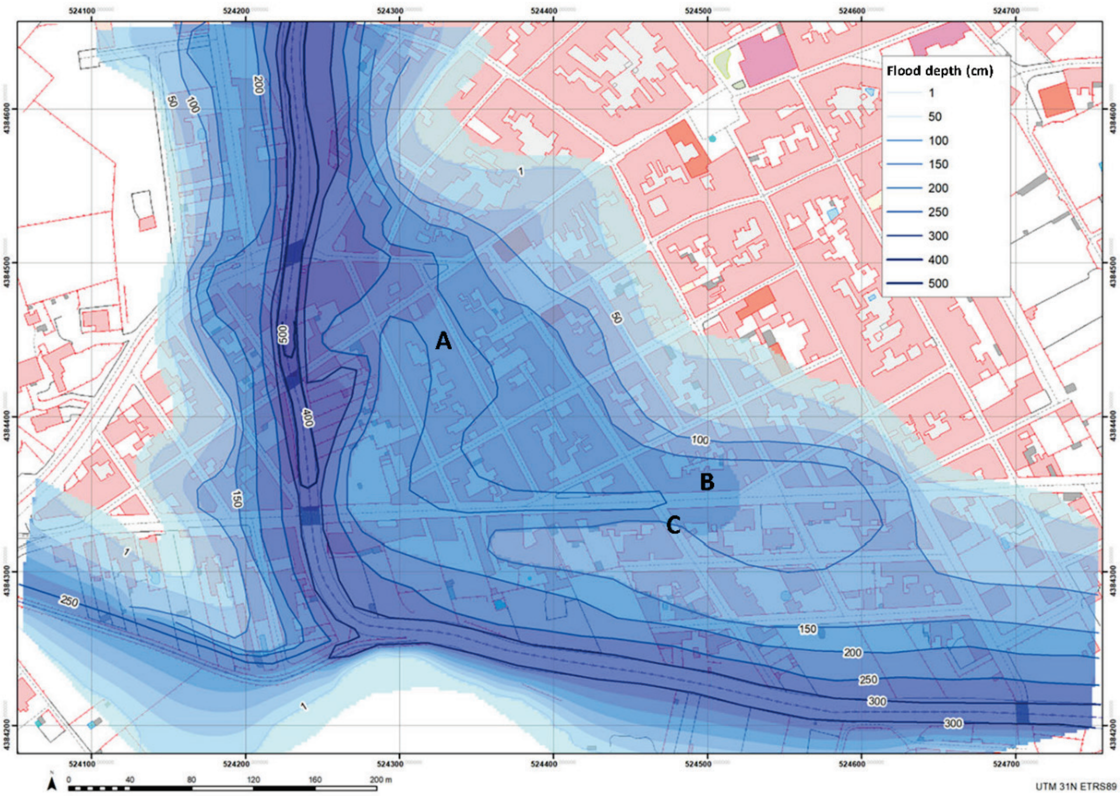

Figure 12. Cartography of the water levels, which were over 1.5 m, mainly in the lower part of the city. This height, together with the remarkable speed of the flow, resulted in the water swiping parked cars, as well as favoured water to smash doors and windows, flooding the interior of dwellings. The urban flooding also killed two people in buildings located in Ordinas street (A) and on the road to Son Servera (B). Three more people were killed in their vehicles, the first one in the bridge Pont de Son Mitjanada, and the second one in the road to Son Servera (C).

4.3.4. Obstructions of the water course and their effects

The behaviour of the flood in the urban area is related to several circumstances that combine the natural features of the terrain with the urban layout and some other isolated factors which hindered the watercourse (Fig. 13).

Figure 13. Image of the flood in the bridge Pont de Can Gostí minutes before the peak. The water flow is diverted by the warehouse adjacent to the watercourse (a). The peak of the flood was 2.8 m above the pavement (b).

The flood, hydrologically, is reduced to two avulsions in meandering sections of the *torrent*. In which the overflow water bypassed the meander and flooded a plain area, where the low part of the city and the sporting facilities are located. This scenario was worsened by the lack of capacity of the canal built in 1990, and by the presence of estate dividing walls in rural areas.

The lack of span of the bridges also obstructed the watercourse, since it made the water level rise and led the overflow water out of the canal. In other occasions, the bridges complicated the reintegration of the overflow water to the main course.

The warehouses and factories built in the 70s and 80s next to the water course also prevented the overflow from reintegrating into the main course. The effect of buildings is even more significant when located next to bridges, where the disturbance is maximal. The buildings in the surroundings of the bridge Pont de Can Gostí and next to the road to Son Servera had a detrimental role in the flooding of the village (Fig. 14).

The streets that are parallel to the course transformed into hydric channels. The urban development determined that some of the streets are crossed by other streets, buildings, or walls. These interruptions block the reintegration of water to the main channel and divert it towards other roads, which turns them into fluvial channels that do not respond to topography. These roads prolonged the flood to the east.

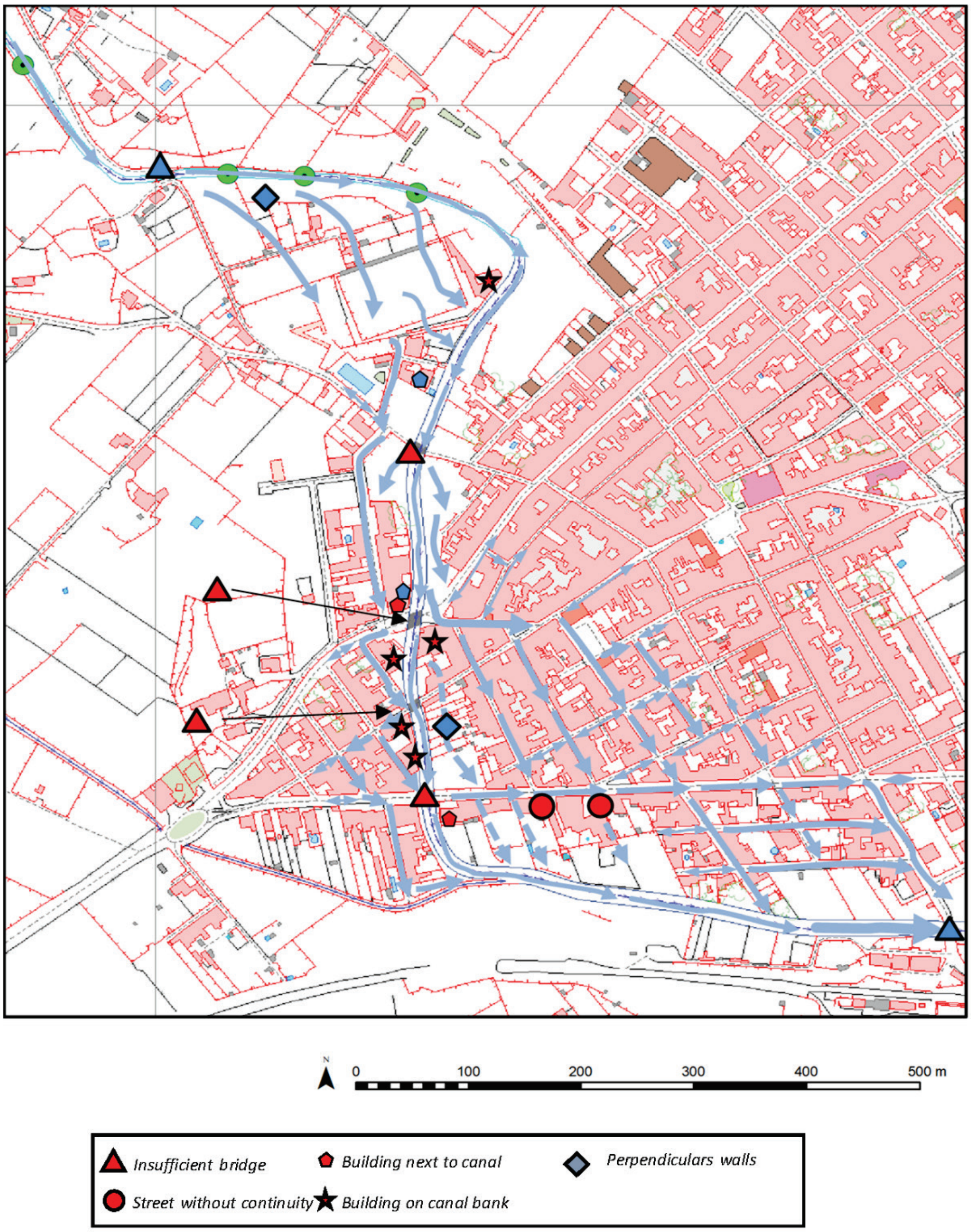

Figure 14. Topographic classification of the main obstacles and interferences to the watercourse in the urban area of Sant Llorenç des Cardassar.

5. Discussion and conclusions

The Sant Llorenç event is framed in a regional context of increased urban floods in Spain (Arranz, 2008), especially in coastal tourist areas (López *et al.,* 2019). However, a set of factors make it a non-exemplary case: an urban area built for almost a century, a population center specifically not dedicated to tourism and an area with previous actions aimed at preventing floods and a basin that has not had radical changes in land use in recent decades. The very high number of fatalities, as well as the affectation of a large part of the population nucleus, highlight the danger of a large part of the Mediterranean area where events with a period of recurrence not well known can have extremely catastrophic effects.

The flood of 2018 has been the most severe one suffered by the village of Sant Llorenç in the last 80 years, with flow peaks over 500 m^3/s. However, the rising was not an extreme event of flash-flood since it did not instantly rise as it happened in 1998. The peak was relatively long and progressive in a span of time of about 15 minutes.

Sant Llorenç is located in an area where several watercourses join. The historical location of the village was not threatened by flooding, benefitting from a hill, and it was surrounded by the course of *torrent* de Ses Planes. The meanders of *torrent* de Ses Planes favour natural processes of avulsion in which the overflow bypasses the meanders and invades its lowest Banks.

The historical settlement of Sant Llorenç expanded moderately in the first half of the 20th century when the surroundings of the watercourse were urbanised following an orthogonal plan. The streets running north to south are parallel to the water course and have a similar slope. This expansion was previous to the demographic growth of Mallorca as a consequence of touristic development in the 60s.

The main part of the buildings next to the watercourse had been built previous to the first flood that have affected the area since 1943. Several floods after this date put into manifest the danger of the low part of the village, but before that, there is no historical record of risk.

The administrative response to the floods has been the building of artificial cemented canals, which have been increasing in capacity after each flood. However, the channels have always been designed with an inferior capacity to the floods registered. The channels have been complemented with bridges with a narrow stem and extremely solidly built, which has worsened overflow and flooding.

The research and analysis of the 2018 flood shows that streets in the city centre constitute subsidiary watercourses in flooding events. These alternative watercourses usually flow following the natural overflowing lines and the topography of the area. However, the insufficient span of bridges, the buildings surrounding the channel, and the interruption of the streets that carry water provoke detrimental processes: they increase the level of overflow towards the streets and also hinder the reintegration of overflowing waters to the main watercourse.

The demolishing of unnecessary bridges, the widening of the span of the elemental bridges, the suppression of surrounding buildings, and the opening of the streets that act as watercourses, would diminish the area of affectation and the intensity of floods.

As a result of the previous actions, the village would have a dynamic hydric circulation of water which would allow water to flow, regardless of the possible insufficiency of capacity of the main channel. Overflowing waters could flow smoothly, and flood levels would be less critical and would not expand to such a wide area.

Acknowledgements

The authors would like to express gratitude towards everyone who has contributed with images, videos, witnesses and experiences, which are vital to reenact the flood event. The city council of *Sant Llorenç* has commissioned several technical reports about the flood, which have been the base for urban remodelling and improvement, the results of which are partially shown in the present paper.

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