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Historical flood events in the Tagus estuary: Contribution to risk assessment and management tools

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ABSTRACT: Flood risk assessment in estuaries requires validated approaches that are able to integrate the multiplicity of hazard forcings. Historical events are valuable in improving the knowledge about flood characteristics and their impacts. The present study aims to present a preliminary analysis of flood event triggers based on historical data. A geodatabase was constructed based on national newspapers, databases and photographic archives from national institutions, and includes 236 occurrences corresponding to 46 events. Flood events are particularly distributed between October and February and associated to multiple flood triggering factors particularly rainfall combined with deficient urban drainage conditions. This study provided a good insight about the contribution of different forcing mechanisms in Tagus estuary flood events which information is both useful for flood forecasting validation, and management purposes as future land use planning. In future work, comparison with instrumental data will enable the assessment of historical data sources uncertainty.

1 INTRODUCTION

Flood risk management and adaptation strategies require accurate hazard prediction to support the assessment of potential losses and consequences (Simonović 2012). Successful efforts have been made in recent decades to develop accurate and timely flood predictors, particularly for river floods and coastal floods along open shores (Vanderkimpen et al. 2009, Ghimire 2013, Fortunato et al. 2013).

In estuaries, flood forecasting is still a challenging task due to the lack of suitable methodologies to cope with the interaction of different hazard sources as tides, river flows, wind and waves (Cluckie et al. 2000). Hosting important urban areas along its margins, estuaries present high risk to flooding (Morris et al. 2013, Carrasco et al. 2012), well demonstrated by the economic and human impacts of recent events, such as the hurricane Katrina (2005) in New Orleans (Miller et al. 2015), the storm Xynthia (2010) along the French coast (Bertin et al. 2014, Andre et al. 2013) and the hurricane Sandy (2012) in New York (Aerts et al. 2013). Flood risk is expected to increase with changing climate (Allison et al. 2009), and in estuaries sea level rise and growing storminess (IPCC 2013) will intensify flood events (Bilskie et al. 2014). Moreover, human pressure development in estuarine margins will enhance the impact of extreme water levels and risk exposure.

Information of past flood events can contribute to improve the knowledge about flood drivers, event characteristics and associated impacts with particular emphasis on the pre-instrumental period (Barrientos & Rodrigo 2006, Bayliss & Reed 2001). Several databases including historical floods events are available, differentiated by the scale of approach and the inclusion criteria (Mysiak et al. 2013, Santos et al. 2014), mainly for risk management (eg. Kron et al. 2013) and emergency purposes (eg. EM-DAT 2013).

In Portugal, about 75% of the population lives in the coastal region. Most of the major cities, including the capital, are located in the vicinity of estuaries.

Located in the west coast, the Tagus estuary (Fig.1) has an area of about 320 km^2, housing 18 municipalities of the metropolitan area of Lisbon with about one million inhabitants (INE 2012). Estuarine hydrodynamic conditions and water levels are directly influenced by the morphology of the estuary, with a deep and narrow inlet channel and a broad and shallow inner domain where the intertidal area is about 43% of the total estuarine surface (Freire et al. 2013). Due to resonance effects, semi-diurnal tides are amplified within the estuary affecting the distribution of extreme water levels along the estuarine margins (Fortunato et al. 1999, Guerreiro et al. 2015). The influence of the Tagus river discharge, the main source of fresh water into the estuary, in the water levels is limited to farther than 40 km upstream of the estuary mouth (Vargas et al. 2008). Downstream, the water levels are mainly controlled by tides and surges (Guerreiro et al. 2015).

The inlet channel constrains the upstream propagation of ocean waves, while the geometry of the inner domain favours local generation of waves (Freire & Andrade 1999). The morphological settings, hydrodynamic conditions and territory occupation promote high risk of the estuarine margins to flood (Rilo et al. 2013) as confirmed by the impact of past occurrences (e.g. Muir-Wood 2011, Freitas & Dias 2013). For instance, the February 15th 1941 windstorm that is considered the biggest catastrophe in the Iberian Peninsula in the last 200 years, caused human casualties and extensive damages to infrastructures and services disruption (Muir-Wood. 2011).

The main objective of this study is to present the design and preliminary exploration of a geodatabase of historical flood occurrences in the Tagus estuary and to analyze their possible triggering factors. Herein, an "occurrence" designates a geographically defined place affected by estuarine flooding, independently of its severity, which is described or appears in selected data sources (Santos et al. 2014). In order to analyze flood triggering factors all occurrences registered were grouped into events, which are defined by a temporal criterion (Santos et al. 2014): all occurrences with the same date or identified in the newspapers descriptions as being part of the same event are classified as one event.

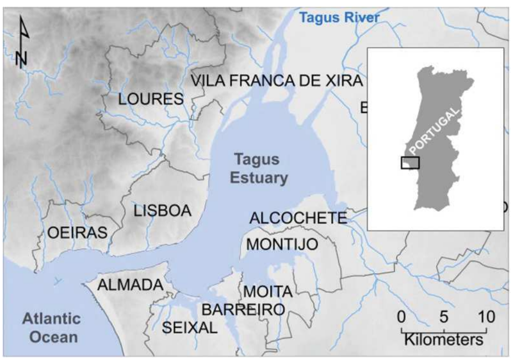

Figure 1. Tagus estuary geographic location and municipality distribution.

2 METHODS

In order to obtain a wide and improved knowledge about estuarine historical floods events, a geodatabase of occurrences was built considering losses, damages and flood triggering factors.

Geographically, the incidence of the geodatabase was constrained to the area where estuarine processes are dominant, between Oeiras and Vila Franca de Xira, the upstream limit of the salt intrusion (Fig. 1). Another inclusion criterion was that the occurrence must be located between the highest astronomical tide line and 20 m above mean sea level and close enough of the margin to be clearly related with the estuarine processes. The highest astronomical tide line was defined and demarcated in previews works (Rilo et al. 2014) for the Tagus estuary and represents the upper limit of the intertidal domain.

Considering that Tagus estuary is framed by Lisbon Metropolitan Area that comprises 18 municipalities and the societal and economical national relevance of this particular area, only national newspapers, databases and photographic archives from national institutions were taken into account as data sources (Table 1). The majority of

Table 1. Sources of information consulted for the geodatabase construction.

	Publication	Coverage period
Source	Typology	(in years)
Newspapers and magazines		
Diário de Noticias	Daily (p)	1864–2013
Jornal de Noticias	Daily (p)	1888–2013
O Século	Daily (p)	1880–1978
Público	Daily (d)	1990–2013
Correio da Manhã	Daily (d)	1979–2013
24 Horas	Daily (d)	1998–2010
Ilustração	Fortnightly (d)	1926–1939
O Século Ilustrado	Weekly (d)	1933–1989
Institutional sources		
APL	photographs	1941–2010
ANPC	geodatabase	2006–2013

(p) – printed source; (d) – only digital source consulted individually for validating and cross-checking purposes; ANPC – Portuguese National Authority for Civil Protection; APL – Lisbon Port Authority newspaper sources were provided by the DISASTER Project (Zêzere et al. 2014) that previously collected all national newspapers with records of hydro-geomorphologic events for Portugal. This information was further complemented in the present work.

The database was organized in four groups of information namely: A) basic relevant data for the event identification such as date and location; B) flood impacts, including casualties, other human losses and property and infrastructure damages or services interruption; C) flood characteristics such as flood extension, depth, duration and speed and D) flood triggering factors namely rainfall, wave characteristics, atmospheric pressure, tidal characteristics, fluvial discharge, urban drainage and other anthropogenic factors identified based on newspapers descriptions.

The information was first collected in a spreadsheet based on geographic coordinates for each event and later introduced in a geodatabase using ArcGIS software. The geographical locations extracted from the newspapers and photographs were georeferenced in ETRS89 PT TM06 based on a toponymy database provided by the National Authority for Civil Protection (ANPC) and a geographical database of Municipalities and Parishes provided by Statistics Portugal (INE). Topographic information was extracted from Portuguese Military Maps series 888, 1:25 000, provided by the Portuguese Military Institute (IgeoE). Furthermore, a set of orthophotographs from 2007 provided by the Directorate-General for the Territory (DGT) (with a spatial resolution of 0.50 m and RGB radiometric resolution) were used for validation and cross-checking control. When required, for old street names and locations, a set of online historical data sources (e.g Hemeroteca, 2015) was consulted.

Overall 147 individual newspapers and magazines were consulted, together with the geodatabase provided by the ANPC and 21 photographs supplied by APL historic archives.

The occurrences extracted from the ANPC geodatabase were filtered by location and by the triggering factors considered in the ANPC internal classification of occurrences. Photograph information was integrated through cross-checking with other online historical sources (e.g Hemeroteca 2015).

In order to assure the consistency of the information gathered in the database, certain rules were taken into consideration: a) the database was filled by one person that read all the news and filled the groups of information; b) when the same event was recorded in more than one source all the information was gathered and compared to obtain more refine details about that event; c) when the source was considered vague, with little information about damages and flood processes, the information was not included;

To assess flood triggering factors only the group D of information concerning the physical causes was analyzed. Considering that the flood events are inde-pendent, a simple probabilistic analysis of the was performed using the Poisson distribution (Santos et al. 2014).

3 RESULTS

3.1 *Flood events*

The geodatabase covers a period from 1865 to 2013, and an area of about 1580 km^2 including 11 municipalities of the Lisbon metropolitan area, between

Oeiras (downstream) and Vila Franca de Xira (upstream) (see Figure 1). In total 236 occurrences were reported (Fig. 2), comprising 46 events. The events frequency and annual probability of occurrence are presented in Table 2. The results reveal that the probability of the occurrence of one or more flood events in one year is 27.4%.

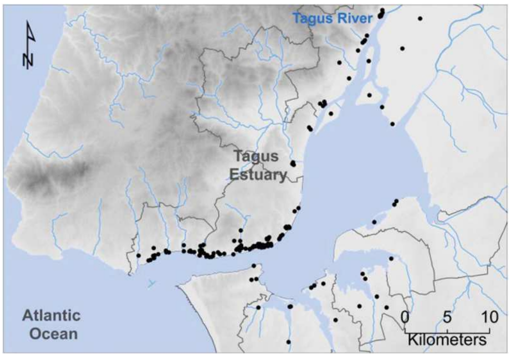

Figure 2. Spatial distribution of database estuarine flood occurrences in the Tagus estuary. The dots represent the location of the estuarine flood occurrences.

Table 2. Events frequency and annual probability of occurrence.

Events	Frequency Abs (nº)	Rel (%)	Probability
0 events	112	75.7	0.733
1 event	28	18.9	0.228
2 events	6	4.1	0.035
3 events	2	1.4	0.004

Note: total number of events = 46; Temporal period = 148 years

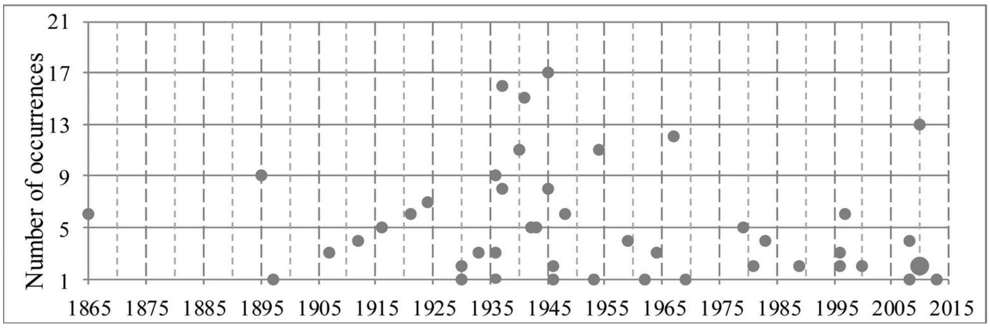

Figure 3. Temporal distribution of annual flood occurrences between 1865 and 2013. The dots represent a different event.

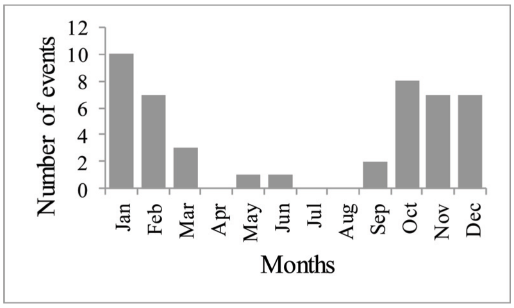

Figure 4. Seasonal distribution of flood events.

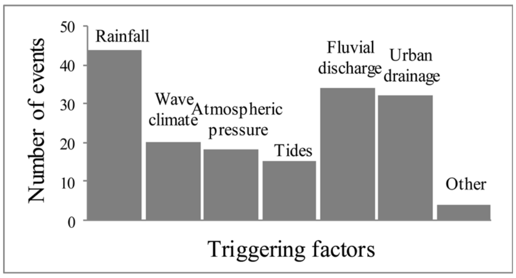

Figure 5. Number of events by triggering factor.

The temporal distribution of flood occurrences and events, expressed in Figure 3, indicates that the maximum number of events recorded in one year was three, in 1936 and 2010. Furthermore, the year 2010 together with 1937 and 1945 registered the larger number of occurrences.

The seasonal distribution of the events (Fig. 4) confirms their high concentration in autumn and winter months (particularly between October and February), which corresponds simultaneously to the rainy period in Portugal and to the period with favorable climatologic conditions for low atmospheric pressure episodes and windy periods. The two events registered in May and June correspond to isolated situations related to short and intense rainfall episodes.

3.2 *Triggering factors*

Results show that almost all the events have more than one triggering factor associated. Figure 5 provides a global vision of the relative importance of each flood triggering factor, according to the database information for each event. Almost all events (44 events correspond to 96% of the total events) are related to rainfall presence immediately followed by high fluvial discharge conditions (74%) and deficient urban drainage situations (70%). Also, wave climate conditions (43%), low atmospheric pressure episodes (39%) and the occurrence of high tide levels (33%) can contribute to flooding events. Finally, with less expression, anthropogenic factors, mainly related to disruption of agriculture protection walls and dykes, also contribute to estuarine flooding (9%). Results show the close interaction between rainfall and urban drainage conditions, since 97% of the events with deficient urban drainage also have rainfall as triggering factor.

Seven events were selected based on the relevance of their impacts that included human deaths, to illustrate the possible association of the flood triggering factors (Table 3). In these examples rainfall and fluvial discharge are always present, followed by tide, atmospheric pressure and wave characteristics.

4 DISCUSSION AND CONCLUSIONS

The present paper demonstrates, confirming other studies (e.g. Zêzere et al. 2014; Santos et al.

Table 3. Selected flood events and triggering factors.

Dates	Triggering factors						
	R	WC	AP	T	FD	UD	O
25 Nov 1865	x	x			x		
15 Jan 1924	x	x	x		x	x	
27 Jan 1937	x	x	x	x	x	x	x
15 Feb 1941	x	x	x	x	x		x
18 Nov 1945	x	x			x		
24 Oct 1954	x		x	x	x		
25 Nov 1967	x		x		x		

Notes: R = Rainfall; WC = Wave climate; AP = Atmospheric pressure; T = Tides; FD = Fluvial discharge; UD = Urban drainage; O = Other; X = present in source description.

2014), that historical data has the potential to give valuable insights on the spatial and temporal distribution of past flood events, on their characteristics and impacts, and on their forcing factors. However, the conclusions taken from this type of sources should be made carefully, particularly if they correspond to an extended time period (from 1865 to 2013). Information reliability depends on the completeness of the database, on the basic definitions assumed as inclusion criteria, and on the intrinsic characteristics of the newspaper sources. These latter might be biased since over time the journalistic criteria to report and publish this type of information has changed. Another important source of uncertainty detected during this study was the influence of the Lisbon municipality social importance, which led to a more diverse and rich descriptions of floods in that area, when compared to others. With respect to triggering factors, the diverse typology of sources combined with the above mentioned causes of bias limits definitive conclusions.

Temporal analysis of flood events indicates that the frequency of flood occurrences and events was higher between 1930–1946. Recently, the year 2010 is worth of mentioning with a high number of occurrences and events.

Historical data point out that flood events in the Tagus estuary are associated to multiple causes and that the heavy rainfall situations combined with deficient urban drainage conditions are the flood triggers more often mentioned. Rainfall is the triggering factor that is mentioned in all events with human losses descriptions. The high number of events related with rainfall and urban drainage (Fig. 4) may reflect the impermeabilization of estuarine margins by urban areas, industrial and port facilities. These results stress the need of coupling between urban drainage and estuarine modelling in future events forecasting. The estuary also frames, in the left upstream margin, a large extension of productive agricultural areas that are below the present mean sea level, separated from the estuary by walls and dykes. Past flood events have strike those areas leading to agriculture land losses. Considering future scenarios of sea level rise, flooding risk of these areas will increase posing new challenges to their planning and management.

The geodatabase described herein provides an important insight into the Tagus estuary, since it is the first time that historical data regarding estuarine flood occurrences is compiled and synthetized, with the specific objective of providing a complete view about the most important flood triggering factors. These preliminary results still have to be compared and validated with instrumental records of flood triggering factors. Future work on historical data will also address flood impacts and characteristics and explore the potential relationship between time, location and triggering factors.

The collected information is both useful for flood forecasting modelling validation and for management purposes particularly future measures of land use planning. The future outcomes of this study might also support specific regional risk assessment studies concerning the large industrial facilities that are located in the Tagus estuary margins.

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