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ARTICLE

Dealing with Multisource Information for Estuarine Flood Risk Appraisal in Two Western European Coastal Areas

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Abstract Estuaries are usually affected by compound flooding triggers that cause diverse territorial damages. While fluvial flood risk assessment frameworks are well established in the literature, integrated management instruments that deal with estuarine flood risk remain incomplete and often lacking. This research presents a methodology to extract relevant information from multiple sources post-event and a database building process that is applied to two contrasting estuaries (the Tagus River estuary in Portugal, and the Shannon River estuary in Ireland) in the Western European coastal area. Overall, a total of 274 documents were analyzed and the information was stored in two databases. Multiple correspondence analysis was applied to extract the most informative and relevant estuarine flood indicators. An integrated estuarine flood risk assessment framework is presented and discussed based on the extracted indicators. The framework is driven by two distinct dimensions (oceanic and hydrographic) and revealed the transversal position of triggers of estuarine floods, reflecting the compounding effects usually present in these areas. The results also highlight two levels of flood risk mostly based on damage typology.

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1 Introduction

As Davidson et al. (1991) pointed out, defining an estuary is not simple and straightforward. Nevertheless, it is widely accepted that estuaries form a transition area that links marine, terrestrial, and freshwater ecosystems commonly located along river mouths, coupling a mix of freshwater and marine saltwater (Pritchard 1967) subject to tidal rise and fall, usually twice a day in the case of European estuaries of the Atlantic coast (Elliot and McLusky 2002).

Flooding processes in these systems are complex due to a combination of natural and human influences, and diverse temporal scales in action (Wu et al. 2021). A wide range of hazard sources act simultaneously in these areas (Hendry et al. 2019) that are also frequently occupied by diverse human settlements, ranging from major metropolises to small cities and commercial/industrial/services areas. Agricultural zones are also very common due to the fertile lands gradually deposited over the centuries by sediments and nutrient inputs from riverine and marine waters that have led to major reclaimed areas and thus to estuarine wetland losses (Vis et al. 2008; Pye and Blott 2014).

Estuaries have been attractive throughout human history, but a wide variety of physical triggers are responsible for flooding, frequently leaving a trail of significant damages (Meyer et al. 2013). To evaluate and assess flood risk in these areas it is necessary to bring to light information regarding triggers and exposure to fully characterize hazard and vulnerability. Historical information can play a significant role (Ruocco et al. 2011), especially with respect to exposure information, but also in enhancing flood frequency estimation or flood model validation (Mei et al. 2018), which are of huge relevance when it comes to assessing events dated before the instrumental period (Baart et al. 2011). Historical information ranging from newspapers to photographs can be especially relevant on damage descriptions and accountability (Santos et al. 2014). The information extracted from these sources is often compiled and organized in databases since they allow queries and assure consistency. Commonly used global disaster databases include, for example, EM-DAT (CRED 2022), and national databases include, for example, the Italian AVI Project (Guzetti et al. 1994), the Portuguese DISASTER database (Zêzere et al. 2014), and the British SURGEWATCH database (Haigh et al. 2017).

The Western European coasts have a wide diversity of transitional water bodies in the mouths of major rivers that are widely affected by Atlantic storms leaving a track of damage records (Haigh et al. 2017; Garnier et al. 2018). While fluvial flood risk assessment frameworks of reference are well established (Merz et al. 2010), frameworks to deal with flooding risk in transitional areas, such as estuaries, remain incomplete and often lacking in the literature. Moreover, international strategies such as the Sendai Framework for Disaster Risk Reduction 2015–2030 (UNISDR 2015) point to the need to develop methodologies capable of measuring vulnerability and risk that focus on understanding risk in all its dimensions to promote more resilient communities (UNISDR 2015). At the European level, Directive 2007/60/UE on flood risk assessment emphasizes integrated risk management approaches, including nonstructural measures.

The use of indicators is a common instrument to reach a wide methodological integration in dealing with vulnerability and risk (Birkman 2007; Nguyen et al. 2016). Indicators have been widely used and accepted, especially to inform management decisions. Numerous studies have used and developed indicators to assess and/or measure a wide range of risks (Azevedo et al. 2017). Although the literature points to different scientific positions regarding indicator weighing and/or selection (Özyurt and Ergin 2010), the review article of Wolters and Kuenzer (2015) on the vulnerability assessment of coastal deltas highlighted that out of 54 studies only 2% presented a validation of results. The more recent article on social vulnerability assessments using indicators and indices by Fekete (2019) also pointed to the need of more research on indicator validation and justification.

Statistical methods are commonly used to reject redundant or non-explanatory indicators in order to obtain a minimum set of coherent and sufficiently meaningful indicators. Although other methods could be used to select indicators, statistical methodologies have the advantage of providing an unbiased approach (Wolters and Kuenzer 2015). Multiple correspondence analysis (MCA) is a multivariate analysis method appropriate to nominal categorical data (Marôco 2014). A historical view of the method development and its relation to other similar techniques is given by Di Franco (2016). The MCA method is frequently applied in explorative-descriptive analysis using mostly qualitative data in different scientific areas, ranging from social science (Bühlmann et al. 2012) to climate change perceptions (Brunette et al. 2018) or safety research (Niza et al. 2008).

In this study, indicators are used to assess estuarine flood risk. Considering the specificity of the study and taking into account that indicators emerge from historical data, the definition of indicators adopted here is the following: Indicators are a set of variables that characterize natural and anthropogenic systems after the hazardous process has taken place. These indicators can be considered validated since they originate from a set of multisource documents that report unequivocal past flood events in the studied estuarine systems.

There is a need for more integrated methodologies to deal with flood risk management that consider the complexity of estuarine water bodies and at the same time contribute to obtaining validated indicators. The present work aims at evaluating estuarine flooding risk using as the starting point two sets of post-event multisource information obtained in two different estuaries on the Western European coasts, the Tagus River estuary in Portugal, and the Shannon River estuary in Ireland. Given the aim of this study, two specific questions were examined:

To what extent can post-event multisource information contribute to obtaining validated indicators to support estuarine flood risk management?

What are the most relevant estuarine flood risk indicators on the Western European coasts?

The ultimate goal is to contribute to an integrated flood risk management approach, not based on general frameworks, but on local-based characteristics that emerge from historical data. Due to their constrasting characteristics, historical records of estuarine flooding, and information availability, the Tagus and Shannon estuaries were chosen as the study areas.

2 Western European Coastal Areas: The Tagus and Shannon Estuaries

Western European coasts have a long history of coastal flooding due to storm surges that often interact with particular estuarine characteristics that result in compound flooding effects with severe consequences (Lamb 1991;

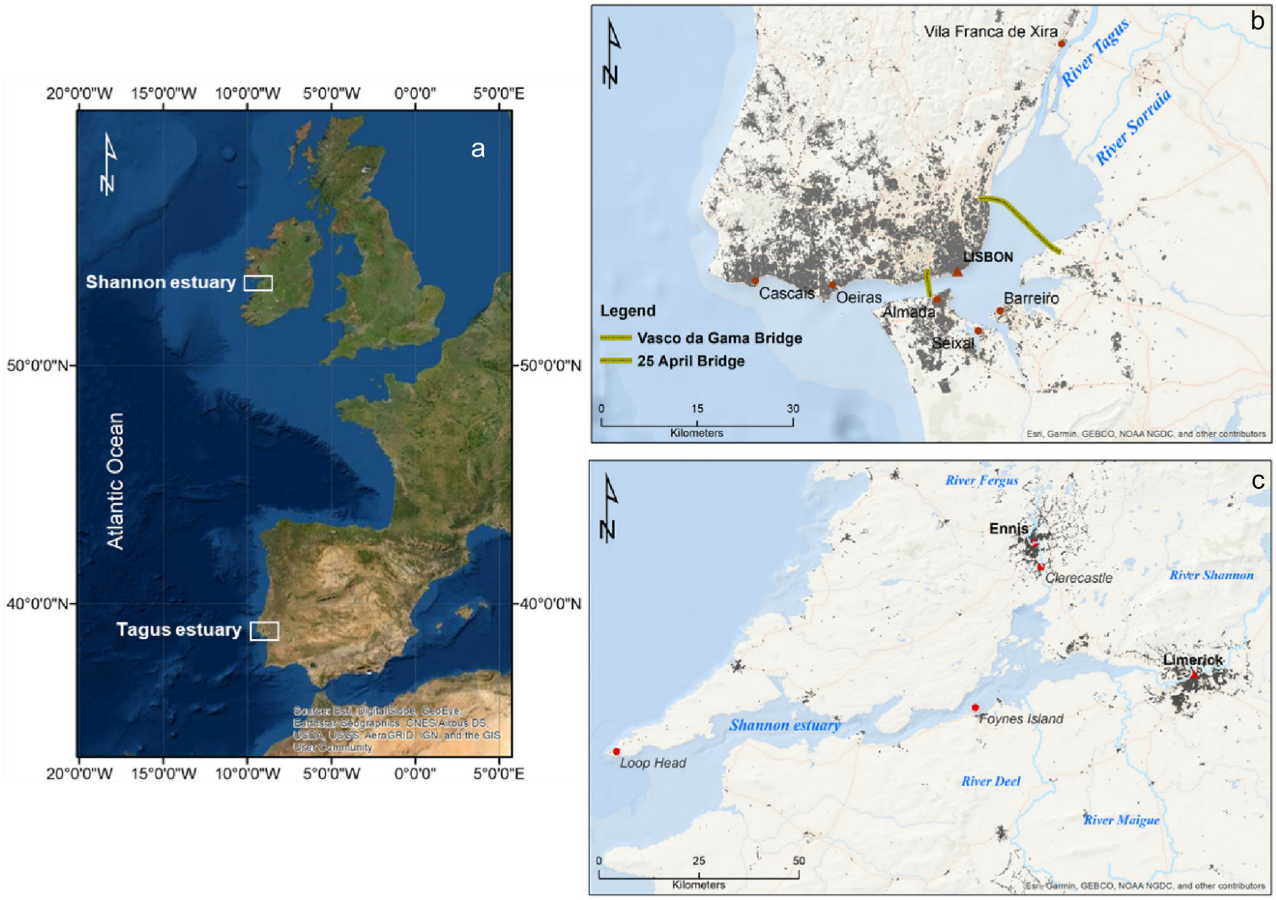

Fig. 1 **a** Geographic location of the Tagus (Portugal) and Shannon (Ireland) river estuaries in the context of the Western European coasts; **b** Tagus estuary main urban areas and rivers; **c** Shannon estuary main urban areas and rivers. *Sources* **a**, **b**, and **c** ESRI Base Maps and Open Street Map.

Garnier et al. 2018). The Tagus and Shannon estuaries on the Western European coasts (Fig. 1a) present different tide ranges and internal morphology, both have records of freshwater discharge, are affected to different extent by storm surge effects, and have distinct levels of artificialization (Fig. 1).These constrasting features make them interesting case studies.

2.1 Tagus Estuary

The Tagus estuary is located in the western part of the Iberian Peninsula, on the west coast of Portugal (Fig. 1a). The Iberian Atlantic coast tides are semi-diurnal and storm surges increase from south to north. Due to direct exposure to the waves coming from the Atlantic Ocean, the coastline is subject to a very energetic wave regime (Fortunato et al. 2016).

The climate in Portugal is controlled by the country's location in relation to the Atlantic Ocean in the north and northwest and the Mediterranean Sea in the south and southwest. The precipitation regime has an irregular pattern in terms of spatial and temporal distribution. According to Trigo and DaCamara (2000), the intraannual precipitation variability can be explained by atmospheric circulation patterns considering the geographic location of Portugal, associated with orographic characteristics and oceanic and continental influences. But several studies (for example, Trigo and DaCamara 2000; Trigo et al. 2002) have shown that the interannual variability is fundamentally controlled by the North Atlantic Oscillation (NAO) and that a NAO negative phase has been demonstrated to be correlated with more wet periods. Benito et al. (2008) found a relation between a negative NAO phase in the winter months and maximum peak discharges for the Tagus River.

The Tagus River hydrographic basin is about 80,629 km^2 (CADC 2022), and the Tagus and Sorraia Rivers (Fig. 1b) are the main sources of freshwater discharge into the estuary. However, the fluvial discharge effect on the estuarine water levels is restricted to estuarine upstream areas (Vargas et al. 2008). Over the twentieth century the Tagus and Sorraia river discharge was modified by the construction of several dams for hydroelectricity production and flood control, both in Portuguese and Spanish territories.

According to Vaz et al. (2020), water depths vary between 0 and 12 m in the shallow inner area and 25 to 30 m in the narrow channel. Water levels in the Tagus estuary are influenced by resonance effects triggered by the estuarine morphology that promotes tidal range amplification (Guerreiro et al. 2015). Wave propagation into the estuary is constrained by the existence of a narrow inlet channel although the geometry of the extensive shallow inner domain can induce local generation of wind waves (Freire and Andrade 1999). Water levels in the estuary can increase due to storm surge effects that have been estimated at 46 and 58 cm at the Cascais tide gauge (closest to the estuary's mouth, Fig. 1b) for return periods of 5 and 100 years (Andrade et al. 2006), respectively. More recent estimations that considered a return period of 100 years and present mean sea level (MSL) quantified water level variations of 4.5 m (CD-chart datum: 2.08 m below mean sea level) in Cascais and 5.1 m (CD) 50 km upstream, in Vila Franca de Xira (Fig. 1b) (Freire et al. 2016).

The Tagus intertidal area comprises among other features intertidal flats, salt marshes, beaches, and salt pans (Nogueira Mendes et al. 2013). Reclamation activities along the Tagus estuary margins throughout history were first linked to farmland necessity, probably before the mid-twelfth century (Pinto and Kondolf 2016). Reclamation for farmland activities was maintained through the centuries especially in the upstream area between the Tagus and Sorraia Rivers (locally called Lezirias), where a large farmstead company still maintains flood protection walls and dikes. According to Pinto and Kondolf (2016), land reclamation to install infrastructure (port and industrial facilities) took place at the end of the nineteenth century and during the first half of the twentieth century, accounting for 397 ha on the Lisbon Municipality waterfront and 236 ha on the south bank to install large industrial units. Today, the Tagus estuary is framed by the largest metropolitan area of Portugal. Comprising twelve municipalities, it is the most populated area of the country. In 2015 the Lisbon metropolitan area had a resident population of close to three million people (INE 2019).

A key feature to understanding the social and economic dynamics between the two margins of the estuary is the intense commuting movements between them and across municipalities (Ferreira 2016) over the three existing bridges (Vasco da Gama Bridge and 25 April Bridge in Lisbon, and the Marechal Carmona Bridge in Vila Franca de Xira), but also by the ferries that daily cross between the estuary margins. Additionally, a dense road network is located along the margins.

Regarding land use, urban areas are extensive in the northern margin while semi-natural and agricultural areas are predominant in the southern margin, particularly in the areas between the Tagus and Sorraia Rivers, which are a classified and legally protected Natural Reserve and Special Protection Area for Birds. Previous studies (Freire et al. 2016; Fortunato et al. 2017) confirmed that the Tagus estuary has an extensive record of estuarine flood events over the last century.

2.2 Shannon Estuary

The Shannon estuary is located in the southwestern part of the Irish coast (Fig. 1a) and is the largest estuary of Ireland. The western coast of Ireland is frequently struck by a very energetic wave climate that is often responsible for coastal flooding (MacClenahan et al. 2001).

The climate in Ireland is essentially controlled by the Atlantic Ocean influencing average temperatures, precipitation, and wind regimes. The west coast is especially exposed to atmospheric depression tracks, but convective and orographic processes are also present and induce spatial and temporal precipitation variability, but in general terms precipitation in Ireland is of low intensity and long duration (Sweeney 2014). Cyclonic, southerly, and westerly airflows are the most productive synoptic conditions that determine spatial variations in precipitation favoring the significant correlation between winter precipitation in Ireland and the winter NAO (Sweeney 2014). Overall, dominant wind directions are south and west (Sweeney 2014).

The River Shannon is the main fluvial contributor to the estuary, although other rivers (Fergus, Maigue, and Deel) also discharge into the estuarine system (Fig. 1c). The Shannon River basin has an area of about 11,700 km^2, which represents almost one-third of the area of Ireland (Wheeler and Healy 2001). The estuary is under the influence of permanent marine inundation comprising the lower part of the Shannon River between Limerick City and the sea and includes the smaller River Fergus estuary, south of Clarecastle (Fig. 1c). The inner estuary comprises the area east and north of Foynes Island while the outer estuary covers the area west between Foynes Island and Loop Head (Fig. 1c) at the estuary mouth (Healy 2002).

According to Wheeler and Healy (2001), water depths vary between about 37 m near the estuary mouth to about 19 m near the confluence with the Fergus, becoming shallower to the east and reaching less than 5 m in Limerick City (tidal limit). At Foynes Island the mean high-water spring tide is about 4.9 m (relative to Ordenance Datum, OD), while the mean high-water neap tide is 3.7 m (OD). At Limerick docks the mean high-water spring tide reaches 5.44 m (OD), while the mean high-water neap tide is 4.04 m (OD) (Healy 2002). The Shannon estuary is a macrotidal system that records the largest tidal range of the

Irish coast with up to 5.44 m at Limerick docks (Sheehan and Healy 2006; SIFP 2013).

The estuarine intertidal system comprises extensive areas of salt marshes and intertidal mud flats that are mostly unvegetated, although some extensions of cord grass occur in places, as well as reed-beds and swamps (Healy 2002). The role of human influence on the Shannon estuary margins and lowlands evolution dates from Neolithic times to the present, as demonstrated by the reference work of O'Sullivan (2001). From the end of the nineteenth century to the first half of the twentieth century extensive drainage and reclamation works were conducted, leading to a reclamation of about 6500 ha for agriculture and other purposes (Healy and Hickey 2002; Hickey and Healy 2005).

The Shannon estuary margins are occupied by agricultural areas, as well as port (Foynes Port, near Foynes Island) and industrial facilities, and small villages. The main urban center is Limerick City, which according to CSO (2017) had a population of about 94 thousand people (including suburbs) in 2016, followed by Ennis with about 25 thousand people. Foynes Port is an important asset to the economy of the country since it is the second largest Irish port in operation after Dublin Port, and able to accommodate the largest vessels (SIFP 2013) due to the deep estuary waters. Marine tourism, fishing, and aquaculture are other activities within the estuary. The Shannon estuary also holds important natural values, with a Special Area of Conservation (SAC) under Habitat Directive (Lower River Shannon), and the entire estuary as far west as Foynes is a SAC under Birds Directive (SIFP 2013).

In terms of accessibility the estuary has an international airport (Shannon Airport) halfway between Limerick City and Ennis and a set of national and municipal roads that encompass the estuarine area linking the major villages and towns, and local roads linking the small villages. The only bridges are located in Limerick City urban area in the upper estuary and connect the north and south bank of the Shannon River.

O'Brien et al. (2013, 2018) presented a catalogue of extreme wave events for Ireland for the period of 14,680 years BP to 2017 that confirms the relevance of extreme wave events affecting the Irish coast, including storm surges (understood as a long-period wave by the authors). The magnitude and frequency of storm surge events in Ireland between 1961 and 2005 are also emphasized by the Irish Coastal Protection Strategy Study (OPW 2013).

3 Methods

The methodological approach followed in this study is summarized in Fig. 2.

3.1 Information Extraction: From Data Sources to Content Analysis

The study started with data sources compilation for both estuaries. In the Tagus estuary case a set of documents was provided by the DISASTER project[1] that systematically collected daily newspapers with news of hydrogeomorphologic disasters that occurred in Portugal between 1865 and 2010. This set of 168 documents constituted the main source of information for the Tagus estuarine system and was completed with the analysis of newspaper sources until 2013 and two other institutional sources (Table 1).

The Shannon estuary data sources were downloaded from the former Irish Flood Hazard Mapping Website (which moved to the recent national flood information portal launched in 2018) that through an interactive platform provided past flood event records from the national flood data archive until the autumn of 2014. More recent events are now being uploaded to the new website (OPW 2020).

In this study we used only the sources from the old website (until autumn 2014). Website statements of use inform users that the data were collected by the Office of Public Works (OPW) from local authorities, other state bodies, and members of the public, and do not constitute a comprehensive and complete catalogue of all events. Users are also advised that the data only reflect flood events with a fluvial, tidal, or coastal origin, and newspaper sources only reflect the most severe events in the past 120 year. Assuming these conditions, a total of 106 diverse documents were gathered ranging from reports to newspapers and photographs.

Content analysis techniques were applied to extract information from the collected sources (Fig. 3) based on Krippendorff (2004), Bowen (2009), Krippendorff and Bock (2009), and Wei et al. (2015). This was done with an extensive reading of each individual document supported by a previously designed coding table that defines the variables, the type of field in the database for each variable, their description, and operational notes (Krippendorff 2004; Krippendorff and Bock 2009). Finally, the information was extracted following the coding table (Fig. 3).

3.2 Building the Databases

The process of content analysis allowed the extraction of relevant information that was stored in a database, which was structured into different groups of information: document information (such as source, date); geographic information (such as location, and the geographic coordinates when possible); flood characteristics information

[1] http://riskam.ul.pt/disaster.

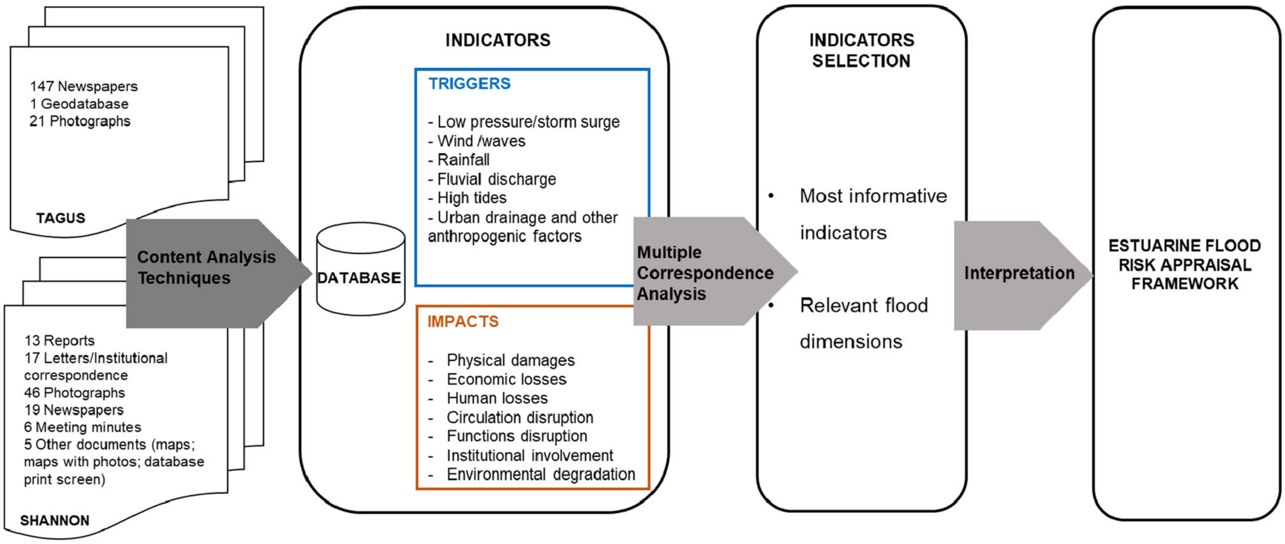

Fig. 2 Methodological framework used to obtain validated indicators for estuarine flood risk appraisal

Table 1 Sources and typologies of the documents consulted for the two estuarine systems in Portugal and Ireland

Source	Typology	Temporal coverage (Years)
Tagus Estuary		
DISASTER project collection of newspapers	Daily, fortnightly, weekly	1865–2013
National Authority for Civil Protection (ANPC)	Geodatabase	2006–2013
Lisbon Port Authority (APL)	Photographs	1941–2010
Shannon Estuary		
Irish Flood Hazard Mapping Website (Office of Public Works)	Reports	1927–2014
	Letters and other	
	Institutional correspondence	
	Photographs	
	Newspapers	
	Meeting minutes	
	Other types	

(water depth, extent when available); triggers information (such as high tides, waves, wind, fluvial discharge, low pressure / storm surge); and damages information—such as physical damages in infrastructures, human losses (deceased, missing, injured, evacuated, displaced, confined, and homeless people) or circulation interruption.

To assure that flood events were due to estuarine conditions, two different procedures were performed, depending on the estuarine system. In the case of the Tagus estuary, the geographic incidence was constrained between Oeiras and Vila Franca de Xira, which corresponds to the upstream limit of salt intrusion (see Fig. 1b), and between the highest astronomical tide line (Rilo et al. 2014)—the upper limit of the intertidal domain and 20 m above mean sea level (Rilo et al. 2017).

In the case of the Shannon estuary, a previous extraction was done (see Fig. 3) to remove the documents that were not related to estuarine floods. This extraction was done using documentary proxies that inform about the areas subject to estuarine flood events (considered as the combination of fluvial and coastal flooding), that is, the OPW website[2] and the information of three reports (Jacobs 2012a, 2012b, 2012c). We only considered events that affected the area between Loop Head and Limerick City (tidal limit) (see Fig. 1c) and whose description was clearly connected with estuarine flooding.

Each database entry was defined by the set of information extracted from the analyzed sources, comprising document, geographic, triggers, and damages characteristics from a given estuarine flood event in a given location.

[2] http://www.floodinfo.ie/map/floodmaps/.

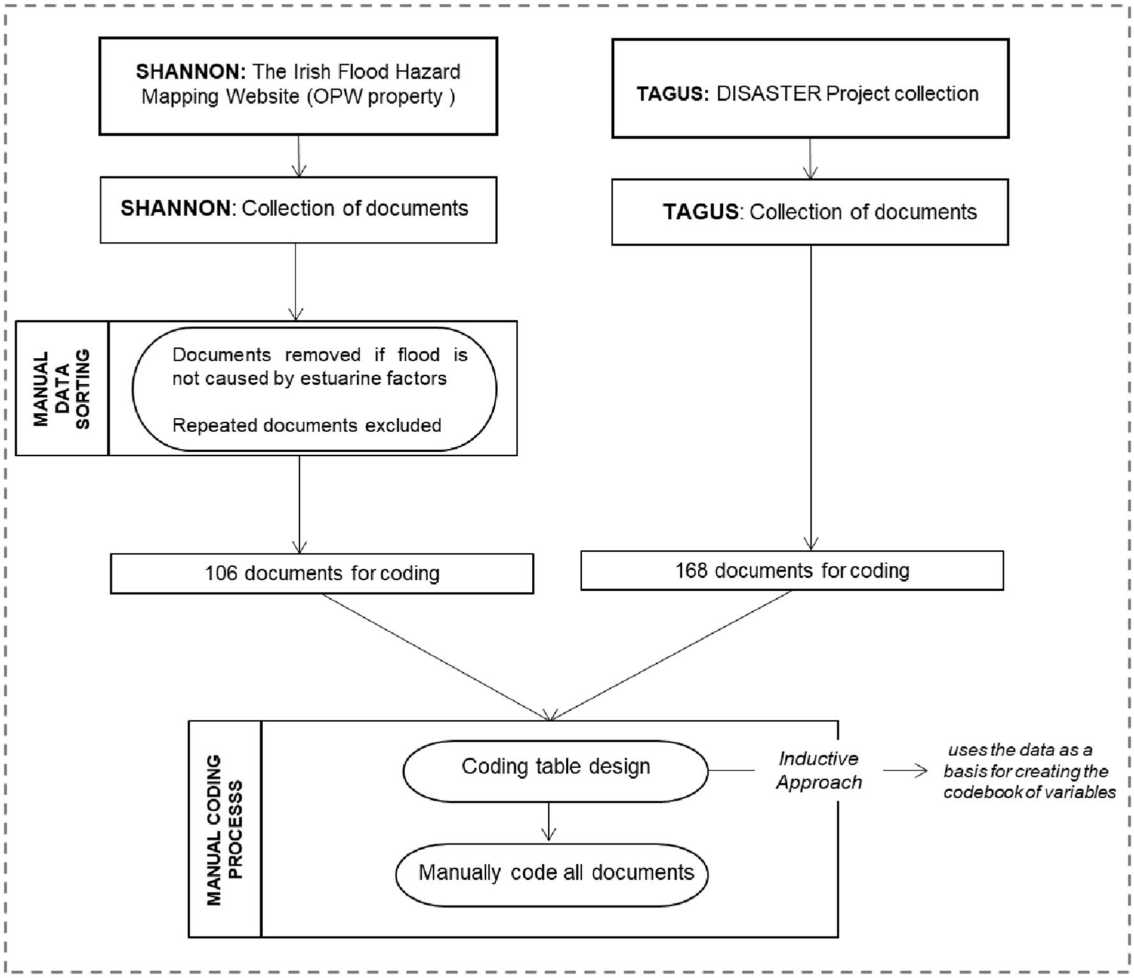

Fig. 3 Methodological framework for information extraction using context analysis applied to the Tagus and Shannon River estuaries. *Source* Based on Wei et al. (2005).

The presence or absence of a trigger or impact is registered within a boolean field (yes—1; no—0) and when available detailed information (for example, wave height or number of flooded houses) is registered in a text field. Since the two databases for the Tagus and Shannon estuaries share the same structure and were built using a similar framework for information extraction (see Fig. 3), they were merged into a single database comprising a total of 465 entries, 235 for the Tagus estuary and 230 for the Shannon estuary.

3.3 Statistical Analysis

A multiple correspondence analysis (MCA) was applied to the triggers and damages fields of the merged database using IBM SPSS Statistics software. Multiple correspondence analysis is a nonlinear multivariate analysis method (Gifi 1996) appropriate for nominal categorical data (Marôco 2014; Carvalho 2017) that allows the visualization and detection of underlying data relationships (so-called dimensions in MCA) and possible associations in data individuals (in this case database entries) and variables, providing simultaneously the most informative variables and therefore offering the basis of an informed decision on variable exclusion. The SPSS software uses a procedure developed by Leiden University called "optimal scaling" using the alternating least squares method (Meulman 1992) that attributes numerical values to each category of a qualitative variable (Marôco 2014).

For clarity some definitions are given here: variables (represent indicators—for example rainfall or economic losses) are characterized by categories (in this case the presence/absence of a certain trigger or damage), and each database entry is an individual or object. Multiple correspondence analysis starts with a study on how many dimensions should be retained (Carvalho 2017) in order to proceed with the analysis. This procedure was done calculating the maximum number of dimensions, which is given by Eq. 1:

$$r_{\max} = \min\{(n-1); (p - \max(m_1; 1)\} \quad (1)$$

where: $r_{\max}$ = maximum number of dimensions, n = total number of individuals or objects, m_1 = number of variables without non-answers.

Since the number of invidual (465 database entries) is greater than the number of categories (2), the expression can be reduced to $p - \max(m_1; 1)$. Therefore the database has 13 variables without non-answers ($m_1 = 13$) with two categories each, thus $p = 26$. The maximum number of dimensions is $p - m_1$, hence 13 dimensions. The MCA was performed with 13 dimensions and the analysis revealed that the first two dimensions were the most representative in terms of inertia (ratio between eigenvalue and total of active variables). Therefore the model was run again but with only two dimensions.

4 Results

Rilo et al. (2017) tested a set of database fields to characterize estuarine flood risk for the Tagus estuary demonstrating its usefulness, thus the same fields were considered to build the Shannon database, setting a uniform structure for both estuarine systems. In this study the two databases were merged into one estuarine flood damage database reflecting the flooding processes and corresponding damages in two different systems. Nevertheless, a brief appraisal of each database and the consulted sources is given here.

The Tagus database has a total of 235 entries and was mainly built based on newspaper sources (90.2%, relative to the total database entries) comprising a continuous period of 148 years between 1865 and 2013. The database is therefore well represented in temporal terms, although as previously highlighted (Rilo et al. 2017) it is recognized that this type of source is not the most appropriate to extract information about triggers, since it is relatively imprecise due to the intrinsic characteristics of these sources. But newspaper sources are quite reliable on damages description and accountability. In terms of spatial distribution, the estuarine flood events are more concentrated in the north margin municipalities. This reflects the social importance of Portugal's capital and the adjacent areas over the last century (Rilo et al. 2017).

The Shannon database has a total of 230 entries that were extracted from a diversity of sources: 27.4% from reports; 22.2% from institutional correspondence; 20% from photographs; 18.3% from newspapers; 8.7% from meeting minutes, and 3.5 % from other sources (maps). Nearly half of the database entries (114 out of 230) come from reports and institutional correspondence—these sources have a large amount of useful information. In terms of temporal coverage, the database is not uniform, with periods with no entries. This does not necessarily mean an absence of flooding events, considering that the original source of the documents (the OPW website) assumes that the collection is neither exhaustive nor complete. In terms of geographic coverage, the database reflects the social importance of Limerick City in the Shannon estuary margins, since more than a half of the entries (56%) are from that urban area.

A multiple correspondence analysis was performed to obtain the most informative indicators, possible relations between database entries and simultaneously the dimensions that might characterize estuarine floods in terms of triggers and damages. The model summary presents a mean Cronbach's alpha of 0.650 (Fig. 4). The Cronbach's alpha confidence interval was calculated in SPSS using the procedure described in SPSS (2020) and Bravo and Potvin (1991). The Cronbach's alpha value obtained was 0.648 with a 95% confidence interval ranging from 0.600 to 0.692.

Cronbach's alpha is a widely used measure to study internal consistency of a certain dataset based on input data reliability and ranges between 0 and 1. Several authors—for example, Nunnaly (1978) and Kaplan and Saccuzzo (1982)—proposed different thresholds to consider alpha acceptable. An overall analysis has shown that an acceptable alpha value should be at least 0.7 although a value of 0.6 can be considered acceptable in certain cases (Marôco and Garcia-Marques 2006), therefore the mean alpha value of 0.65 was considered acceptable.

The MCA model summarizes the data in two dimensions. Inertia values for each dimension provide variance in relative terms and range between 0 and 1. Higher values closer to 1 explain more variance for each dimension. The results (Fig. 4) show relatively low values of inertia; however Carvalho (2017) refers to the work of Benzécri (1976) to draw attention to the fact that low values of inertia do not imply that interpretations cannot be made thus the model was considered valid for interpretation.

The initial 13 variables (or indicators) considered in the model and their discrimination measures are presented in Fig. 4. Discrimination measure values range between 0 and 1, with the values closer to 1 being the ones that better discriminate the dimension. Variable selection is conducted considering the inertia value for each dimension.

According to Carvalho (2017), variables with discrimination values above inertia values for each dimension should be retained. In contrast, variables that present discrimination values bellow inertia values should be excluded. Hence, the variables economic losses and human losses (see Fig. 4) were excluded since they present low discrimination values (closer to 0 in the case of economic losses), when compared to each dimension inertia.

Model summary

Dimension	Cronbach's alpha	Variance accounted for		
		Total (eigenvalue)	Inertia	% of variance
1	0.735	3.114	0.240	23.952
2	0.509	1.886	0.145	14.505
Total		4.999	0.385	
Mean	0.650[a]	2.500	0.192	19.228

a. Mean Cronbach alpha is based on the mean eigenvalue

Discrimination measures

Variables	Dimension		Mean
	1	2	
Rainfall	0.523	0.005	0.264
Wind / waves	0.199	0.379	0.289
Low pressure	0.216	0.274	0.245
High tides	0.002	0.555	0.278
Fluvial discharge	0.434	0.000	0.217
Urban and others	*0.226*	0.055	0.140
Physical damages	0.306	0.090	0.198
Economic losses	**0.014**	**0.006**	0.010
Human losses	**0.183**	**0.109**	0.146
Circulation interruption	0.264	0.023	0.143
Functions disruption	0.469	0.005	0.237
Environmental degradation	0.097	0.177	0.137
Institutional involvement	0.181	0.208	0.195
Active total	3.114	1.886	2.500
% of variance	23.952	14.505	19.228

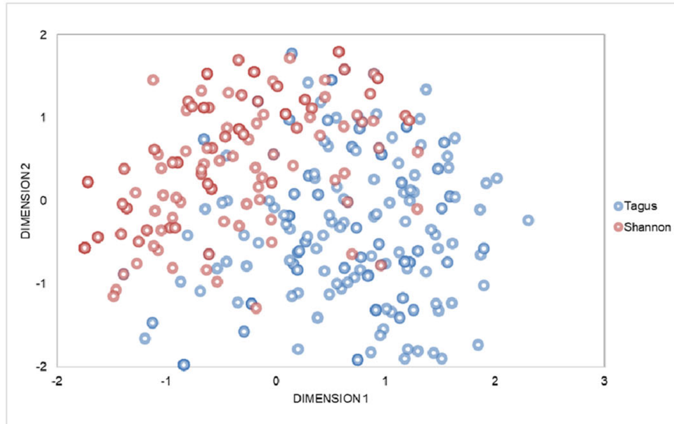

Fig. 4 Multiple correspondence analysis model summary, discrimination measures, and graphic representation of all database entries by estuarine system and their relationship with each dimension (Dimension 1: Hydrographic basin influence; Dimension 2: Oceanic influence). Discrimination measures in bold (economic losses and human losses) are below inertia value for the dimension. Urban and others = Urban drainage and other anthropogenic factors.

Although the variable urban drainage and other anthropogenic factors ("urban and others" in Fig. 4) exhibits discrimination values bellow the admissible, Carvalho (2017) drew attention to similar cases explaining that variables with discrimination values far from zero and closer to inertia value in at least one of the model dimensions can be considered valid if their thematic coherency contributes to dimension interpretation. Thus, this variable was considered.

Overall, MCA allowed not only the graphical representation of all 465 database entries and their individual contribution to explain each dimension by estuarine system (see Fig. 4) but also the preservation of the most informative variables/indicators (eleven) and the retention of the two most representative dimensions (Fig. 5a).

5 Discussion

The following sections discuss the limitations and value of multisource information and propose an estuarine flood risk assessment framework using a set of indicators based on historical data.

5.1 Limitations and Usefulness of Multisource Information

As demonstrated by other studies (for example, Williams and Archer 2002; Ruocco et al. 2011; Haigh et al. 2017), information retrieved from historical sources (ranging from newspapers to institutional reports) provided valuable information about flood triggers and damages, despite the diversity of sources consulted. However, limitations should be acknowledged. For instance, in the Tagus estuary case, newspapers proved to be very detailed in terms of damages descriptions, but often vague in terms of triggers; in contrast, in the Shannon estuary case, reports and meeting minutes provided more details on flood triggers than damages but the information on damages was occasionally completed with newspaper details. This aspect reinforces the idea that the diversity of sources can be very useful to obtain a full picture about estuarine flood triggers and damages. Another drawback is the temporal coverage gap that the Shannon database has in contrast to the Tagus database that has a continuous coverage period. Newspapers, due to their intrinsic characteristics, provide a complete temporal coverage that other types of sources typically do not have. Nonetheless, the results showed that in spite of these limitations, multisource information is

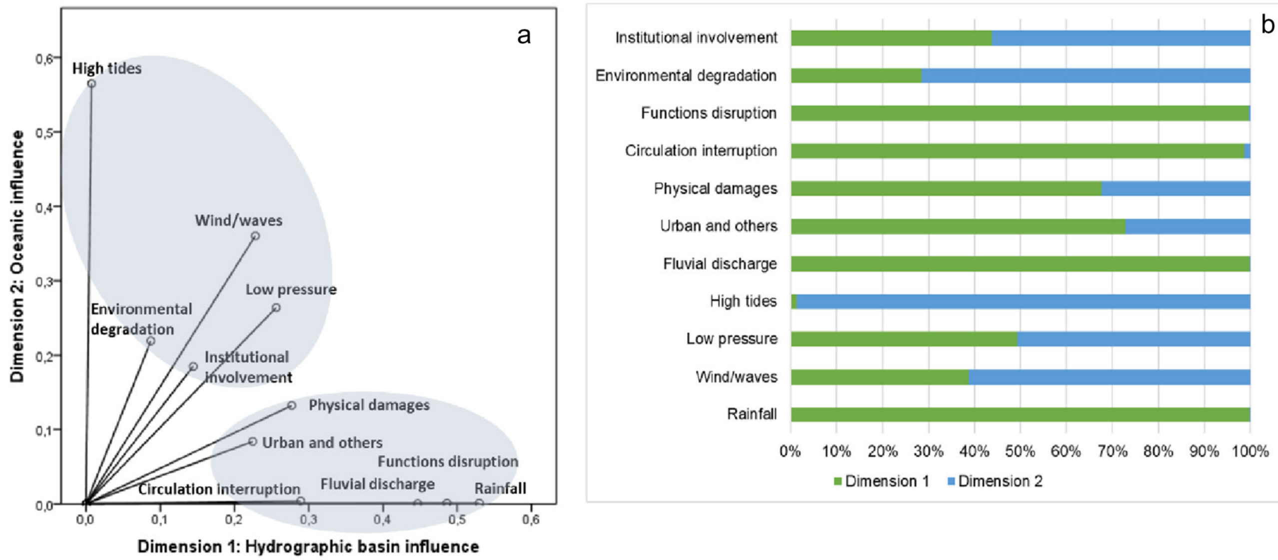

Fig. 5 **a** The eleven most informative variables/indicators and their contribution to each dimension. The oval areas represent the two groups of variables that better characterize each dimension. **b** Variables contribution to each dimension. Urban and others = Urban drainage and other anthropogenic factors.

useful and capable of giving reliable descriptions on past floods, especially when diverse sources can be used to complement each other.

Bearing in mind that indicators in this study are defined as a set of variables that characterize natural and anthropogenic systems after the hazardous events have taken place, each database field can be considered by itself as an indicator. This notion is particularly relevant since it systematizes the presented approach to convert multisource information into indicators.

5.2 Estuarine Flood Risk Assessment Framework

The proposed estuarine flood risk assessment framework was established through a set of indicators based on a previously tested outline (Rilo et al. 2017) capable of characterizing flood triggers and damages. To attain a composite picture on estuarine floods, an MCA was performed using the validated indicators described. The results revealed the exclusion of two indicators (economic losses and human losses), which points to their low capacity to contribute to the thematic interpretation of both dimensions and therefore to evaluate estuarine flood risk in the studied contexts. The exclusion is assumed since the data demonstrated that the presence of economic losses information is quite sparse both in the Shannon and Tagus estuary cases (25 out of 230 entries and 26 out of 235 entries, respectively), as is the presence of human losses information (9 out of 230 entries and 60 out of 235 entries, respectively). Although in the Tagus estuary case the historical record showed that human losses can be relevant (Rilo et al. 2017), they are present only in the context of extraordinary flood events. Nevertheless, these results should be regarded carefully because they are influenced by information quality and availability. Estuarine floods can be summarized by two dimensions—oceanic influence and hydrographic basin influence—whose interpretation depends on the set of variables that support each dimension (Fig. 5a).

Dimension 1 (Fig. 5b, green bars) is characterized by a major contribution of rainfall, fluvial discharge, circulation interruption, and function disruption, and to a lower degree by urban drainage and other anthropogenic factors and physical damages. This set of variables represents the hydrographic basin influence in the estuarine system clearly associated with rainfall and fluvial discharge along with further damage indicators (physical damages, circulation interruption, and function disruption), which are associated with high levels of territory exposure. Dimension 2 (Fig. 5b, blue bars) is characterized by a major contribution of high tides and, to a more limited degree by wind/waves, low pressure, environmental degradation, and institutional involvement pointing to the oceanic influence interpretation.Database entries graphical analysis (see Fig. 4) reveals that although values are widely spread and both estuarine systems contribute to describe the two dimensions, there is a clear trend pointing to the Tagus estuary's major contribution to explaining dimension 1 (hydrographic basin influence), whereas the Shannon estuary contributes more to explaining dimension 2 (oceanic influence). These observations are corroborated by literature on the estuarine dynamics of both systems indicating that the Tagus estuary (see Sect. 2.1) is a

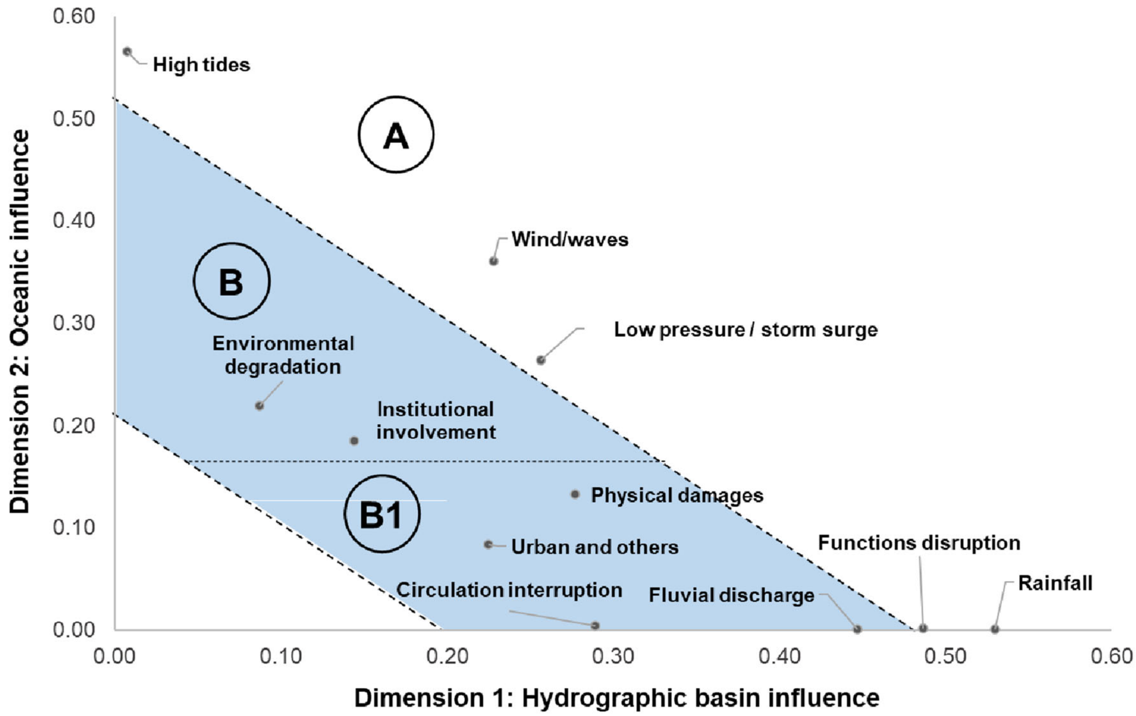

Fig. 6 Estuarine flood risk assessment framework interpreted based on the two dimensions graphical representation. For further explanations on A, B, and B1, see text above. Urban and others = Urban drainage and other anthropogenic factors.

mesotidal system with a limited oceanic wave propagation into the estuary, influenced in the upstream area by river discharges, framed by a large metropolitan area with an intense commuting movement that reflects a high level of assets exposure in the territory. The Shannon estuary (see Sect. 2.2) is a macrotidal system located on a coastline with a very energetic wave climate particularly exposed to low pressure storm tracks. The estuary margins are essentially occupied by agricultural areas, as well as small villages and port facilities. The largest urban center is Limerick City located by the River Shannon mouth in the inner part of the estuary.

The contrast between these two systems is evident, not only in terms of triggers of flooding but also in terms of potential damages, indirectly assessed by the presence or absence of extensive urban and industrial areas and therefore different levels of exposure. Nevertheless, the construction of a common framework to address estuarine flood risk emerging from local contrasting systems was possible, which allows future applications to other case studies and therefore more refined and expanded frames of reference.

The proposed estuarine flood risk assessment framework (Fig. 6) was based on the graphical representation of the two dimensions obtained by the MCA results providing an additional interpretation to the relationship between variables and dimensions. In the proposed framework, area A illustrates that triggers have a significant role in flood risk to both dimensions, denoting the complexity of the compound flooding effects that affect these areas. Area B (Fig. 6, in blue) represents mostly damages. However, environmental degradation and institutional involvement (essentially contributing to dimension 2) can be considered general large-scale consequences in the sense that environmental degradation usually affects extensive areas, and that institutional involvement is a wide-range response. The B1 area is related to more local consequences linked to urban-scale dynamics associated with fluvial discharge, demonstrated by function disruption, circulation interruption, and the lack of urban drainage.

Overall, the proposed framework suggests two types of outcomes in terms of damages—large-scale consequences and more local ones associated with the urban scale, which reflects distinct levels of territory exposure. The two dimensions emphasize the transversal importance of triggers and their complexity and interdependence to estuarine flood risk assessment and that damages are a consequence of both territory exposure and trigger action. The framework also points to the importance of having more tailored measures to manage flood risk in estuarine areas since damages can be distinct in scale and typology.

The proposed framework should be further developed through its application to other contrasting estuaries on the Western European coasts. This will allow indicator confirmation and the proposal of concrete flood management measures that can adequately inform authorities.

6 Conclusion

This study made possible the translation of post-hazard multisource information into indicators through database fields, thus contributing to obtaining a set of validated indicators able to characterize estuarine flood risk. The MCA allowed the selection of the most informative indicators to characterize estuarine floods in two distinct estuaries of the Western European coasts.

In contrast to other approaches, the proposed framework emerged from local-based characteristics that present two dimensions to characterize estuarine floods—hydrographic basin influence and oceanic influence—and revealed the significant importance of triggers but also of damages to better manage estuarine flood risk. The proposed framework suggests that there are two distinct outcomes in terms of damages—large-scale consequences and more local ones linked to urban-scale dynamics that represent different levels of territory exposure associated with different levels of response. These results are a contribution to improving flood risk management since authorities usually use historical data to validate options.

Although we acknowledge that the framework is not suitable for future scenarios planning, including climate change impacts, the obtained set of indicators and proposed framework are a valuable contribution to a more integrated perspective of estuarine flood risk management on the Western European coasts. Future work should include other estuarine systems of these coasts to confirm and expand indicators, and update and improve the presented framework. Future research should also examine the use of the transformed variables resulting from the MCA to perform other statistical analyses in order to expand the knowledge on estuarine flooding risk indicators.

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