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# Enhancing Estuarine Flood Risk Management: Comparative Analysis of Three Estuarine Systems

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**ABSTRACT**

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Estuarine flood risk management is a challenge for coastal managers since this type of system is usually complex due to the presence of multiple trigger combinations that can induce flood events affecting different types of human occupation. Furthermore, legal directives demanded countries to have flood risk assessment tools therefore enhancing knowledge on estuarine triggers and flood damage typologies is useful for coastal managers. In this study three different flood events are compared and contrasted, each one having occurred in a different estuarine system chosen based on a set of criteria (temporal proximity, occurrence of human damages and at least three flood triggers identified in each database). The diversity of data sources that characterizes each database was examined, for the three events, which are described in terms of triggers and damages. The comparison highlighted that the local context was important in the estuarine flood combination of triggers and disclosed two categories (one category comprising infrastructure economic and human damages; and another category involving circulation interruption and functions disruption) of flood damages common between the studied systems corresponding to different levels of relevance for management. The enhanced knowledge acquired allowed the construction of a conceptual framework for damages that can contribute to more adequate estuarine flood risk frameworks.

**ADDITIONAL INDEX WORDS:** *Estuaries, damages, triggers, flood risk management.*

## INTRODUCTION

Estuaries are complex systems lying at the interface between rivers and the sea integrating a multiple combination of flood trigger factors (*e.g.* high tides, storm surges, waves and fluvial discharge) along with diverse land use (*e.g.*, from agriculture areas to dense urban areas).

Estuarine complexity is challenging for coastal managers since flood risk management requires the integration of two contrasting dimensions: flood triggers and flood damages. Therefore, appropriate estuarine flood risk management frameworks are scarce in literature and in practice. In addition, European legal directives recommend that countries develop proper flood risk management tools for this type of water bodies, highlighting the necessity of adequate estuarine flood risk frameworks.

The value of historical information to extract source triggers and damage data has been discussed in literature along with associated limitations (*e.g.* Ibsen *et al*., 1996). It is widely accepted that historical sources, also called "soft data" are helpful in providing details on damages. This information is often organized in flood damage databases allowing further explorations (*e.g.* Zêzere *et al*., 2014).

This study aims to evaluate in what extent is possible to obtain a framework for estuarine flood triggers and damages.

To address this objective the study uses three estuarine flood events selected from different flood damage databases, each one from a distinct estuarine system as a starting point to examine the two contrasting dimensions to flood management: triggers and damages. The study compares and discusses triggers and damage differences and similarities between three different estuaries, allowing a common categorization of damages.

### Study Areas

Three estuarine systems located in the western European coast (Figure 1) were chosen as case study sites: the Shannon Estuary on the west coast of Ireland; the Solent Estuary on the south coast of United Kingdom (UK) and the Tagus Estuary on the west coast of Portugal.

### The Shannon estuary

The Shannon Estuary (Figure 1a) is the largest estuary in Ireland, being framed by a coast with a very energetic wave

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Figure 1. Geographic location of study areas in the western european coast; (a) Shannon estuary; (b) Solent estuary; (c) Tagus estuary. Images: ESRI basemap.

regime and storm surge events (MacClenahan *et al.*, 2001) that frequently generate coastal flooding (O'Brein *et al.*, 2018). Wind and precipitation regimes in the west coast are essentially controlled by the Atlantic Ocean (Sweeney, 2014)

The river Shannon is the main fluvial contributor to the estuary (Wheeler and Healy, 2001) and its lower part, upstream Limerick city is fundamentally controlled by Ardnacrusha dam hydroelectric scheme (Dalton and O'Carroll, 2019). Rivers Fergus and Maigue also contribute to estuary which is a macrotidal system with the largest tidal range along the Ireland coast of up to 5.44m in Limerick Docks (Sheehan and Healy, 2006). Limerick city located in the upstream part of the estuary is on the limit of the tidal influence.

Currently, the estuary margins are occupied by agriculture and industrial areas, a port (Foynes Port, is the second largest in the country) and airport facilities along with small villages. Limerick city is the main urban center with a resident population of about 94 thousand people in the city and suburbs, followed by Ennis with ca. 25 thousand people according to 2016 National Census (CSO, 2016). The relatively dispersed villages along the estuary margins are connected by a network of national and municipal roads and the only bridges linking the two margins are located in Limerick city.

**The Solent estuary**

The Solent (Figure 1b) is a mesotidal estuarine strait (Ozsoy *et al*., 2016) lying between the south coast of UK and the Isle of Wight, in the English Channel. It is a low energy system, comprising 12 separate estuaries and harbors (Fletcher *et al.*, 2007), with an extensive record of flood events (Ruocco *et al.*, 2011). The area is affected by storm surges of heights up to 1m, due to low pressure systems in the Atlantic moving eastward across southern England and also surges coming from the North Sea region (Ruocco *et al*., 2011). The Isle of Wight shelters the estuarine system from the Atlantic westerly waves. The Solent has a tidal range between 2m at Hurst and 5m at Selsey and is recognized for having complex tides particularly the double high waters, which are specially pronounced during spring tides (Wadey *et al*., 2012).

The Solent coastline is densely occupied with up to 1.4 million people living on its margins (Foster *et al*., 2014), being Southampton and Portsmouth the major cities with relevant port facilities and related economic activities, namely commercial, defense and leisure (Fletcher *et al*., 2007). The estuarine margins are also occupied by industrial facilities (*e.g.* oil refinery; power stations) and the water body is extensively used by local population for recreation and travelling through passenger ferries (Foster *et al*., 2014).

**The Tagus Estuary**

The Tagus estuary (Figure 1c) is a mesotidal system located on the Portuguese west coast, with an extensive flood history (Freire *et al*., 2016). The west Portuguese coast is affected by storm surges that increase from south to north, and a very energetic wave regime (Fortunato *et al*., 2016). Water levels inside the estuary are influenced by storm surge effects and by tidal range amplification and resonance due to the peculiar estuary morphology (Guerreiro *et al*., 2015). As a result of a narrow inlet channel the oceanic waves are unable to enter the estuarine domain, although the inner domain geometry favors local wave generation.

The Tagus River is the main fluvial contributor to the estuary and it drains an extensive hydrographic basin that has been modified over the last century with the construction of several dams, which have changed fluvial discharges. Currently the Tagus river margins frame the major metropolitan area of Portugal with twelve municipalities, being occupied by extensive urban areas and agriculture zones in the upstream part of the estuary. According to official data from 2015 (INE, 2017) the Lisbon metropolitan area has a resident population of more than 2 million people. Estuarine margins are linked by two bridges and the water body is used to passenger ferries travelling indicating an intense commuting movement. Public and private companies along with critical infrastructures are located near the margins along with a dense road network.

## METHODS

The methodology followed in the study is summarized in Figure 2. Previous studies (*e.g.* Rilo *et al*., 2017) collected, analyzed and built one estuarine flood damage database for each estuarine system, based on historical sources.

The Shannon database was built from a set of diverse historical sources available on the Irish National Flood Hazard Mapping Website (http://www.floodmaps.ie/). The sources are diverse including institutional documents (*e.g.* reports and minute meetings) and non-institutional documents (*e.g.* newspapers). The database covers the temporal period from 1927 to 2014 and has 230 entries, corresponding to 29 flood events.

The Solent dataset was derived from SURGEWATCH 2.0 database (Haigh *et al*., 2017) of coastal flooding events for the entire UK coast that used oceanographic data complemented with scientific articles, newspapers, weather reports and social media. The Solent database covers the period from 1916 to 2016 and has 77 flood events.

The Tagus database was built based mostly on daily newspaper records previously collected by the DISASTER project and covers the period from 1865 to 2013 with 235 entries. A detail description

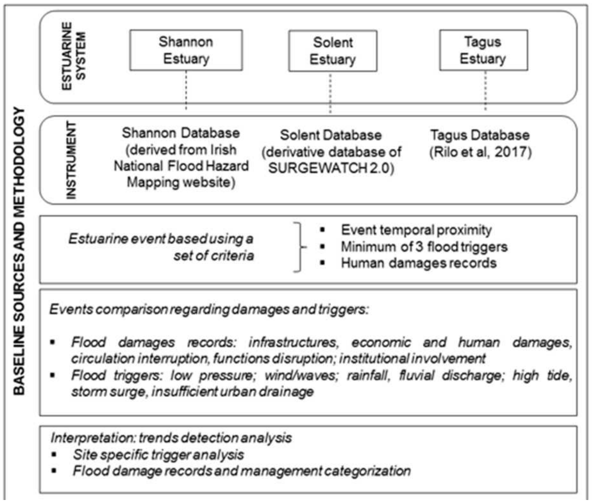


Figure 2. Methodological framework.

of this database is provided by Rilo *et al* (2017), corresponding to 44 flood events.

For Shannon and Tagus databases an event is defined by a set of database entries sharing the same date or identified in the sources to belong to the same flood episode.

To enable comparability all databases have a common internal organization comprising among others the following groups of information: triggering factors and flood damages. Furthermore, the methods to extract information were the same to assure consistency.

A set of criteria for event selection was established to capture a sample of comparable events with temporal proximity, a minimum level of detail information and relevant impact, therefore the following criteria was adopted: (1) the events should be comprised in the period between 1985-2000; (2) a minimum of 3 flood triggers should be identified in each database; and (3) the event generated human damages (referred to damages to people comprising any of the following: deaths, injured, evacuated, missing, displaced and confined people). Based on the above mentioned criteria three events were selected, one from each database, and compared to assess the similarities and differences along the three estuaries.

## RESULTS

The synthesis of flood damages and triggers corresponding to each flood event is presented in Figure 3. The detail description of each event based on the used sources is given in the following sections.

### Shannon Estuary Flood of 24 and 25 December 1999

According to the consulted sources the event was caused by a set of triggers that include: very low atmospheric pressure with possible storm surge, waves caused by strong westerly winds, heavy rainfall, high flow rates in river Shannon and local tributaries which led to dam discharges, spring tides and deficient urban drainage.

The sources described damages in infrastructures, such as flooding of residential and business properties. Specifying damages included to furniture, floor covering and fittings. The sources also reported thousands of pounds of economic damages along with human damages related with confined people into their homes and 1 evacuee. The transport interruption was associated with flooded roads that left areas isolated (cut off) for days. This led to disruption to business along with absence of electricity. A set of institutional entities were involved, namely fire brigades, sanitary services, army and civil defense.

### Solent Estuary Flood of 6 to 8 April 1985

The event was caused by low pressure (980mbar) with associated storm surge effects (0.39m in Newlyn) and spring tides coincidence. The sources were unaware of wave conditions, but mentioned strong southerly winds. Moreover, the sources did not indicate any information about fluvial discharge or rainfall. The sources described damages to infrastructures such as resident and non- resident properties. The existence of economic damages was inferred since there was evidence of flooded properties. Human losses were related with confined people inside their vehicles along the roads. The circulation interruption was associated with flooded roads, which conducted to disruption on circulation. The SURGEWATCH 2.0 database did not mention any institutional involvement.

### Tagus Estuary Flood of 2 November 1997

According to the sources the event was caused by high fluvial flow rates associated with dam discharges coupled with high tides coincidence and a deficient urban drainage. The sources did not mention any information about atmospheric pressure and storm surge, wind and wave presence.

The sources described damages to infrastructures such as residential and business houses. The existence of economic damages was inferred due to flooded properties evidence. Human losses were related to evacuated people. The circulation interruption was related with one tunnel under a circulation passage closed during several hours along with roads, which conducted circulation disruption. Fire brigades and municipal authorities ensured institutional involvement.

## DISCUSSION

Overall the comparative analysis of the three events revealed that the historical sources used to build the databases reflect the damages dimension with more detail then the triggers dimension. These aspects have been discussed by other authors (*e.g.* Rilo *et al*., 2017; Ibesen *et al*., 1996) emphasizing the large amount and detailed information about damages that historical sources are able to give and on the other hand point to the limitations regarding triggers descriptions. Nevertheless, it is worth mentioning the relevance of these type of sources since they provide an overall framework on flood event characteristics.

The comparison of flood event triggers synthesized in Figure 3 highlights different combinations of flood event triggers depending on the estuarine system. The Shannon Estuary flood event (December 1999) was triggered by all forcing factors considered to evaluate estuarine flooding reflecting the relevance of the geographic position relative to the Atlantic Ocean influence (southwesterly winds, low pressure and related storm surge effects along with influence on precipitation and wind patterns). Fluvial discharge into the estuary is determined by the hydrographic basin behavior and precipitation regimes along with dam discharges; which also occurred during this event (see results). High tides

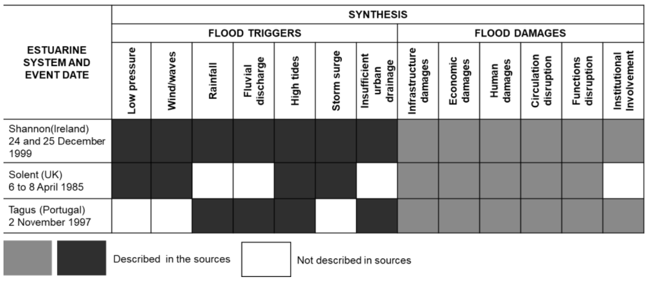


Figure 3. Synthesis of flood triggers and damages for each event.

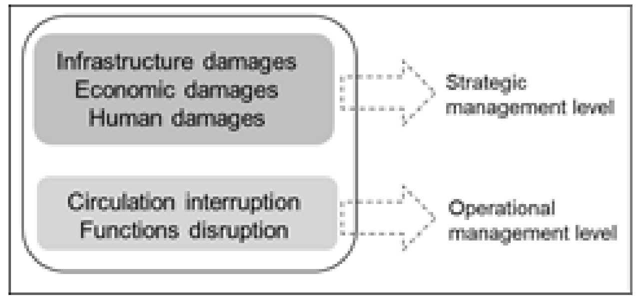


Figure 4. Damages typologies categorization and their relation to different management levels.

were also relevant for the process of flooding since this event occurred during spring tides in a macroestuarine system. Part of the damages where registered in Limerick city, which explains the highlighting of deficient urban drainage as a trigger.

The Solent Estuary flood event (April 1985) displayed a combination of four forcing factors reflecting the geographic position between the Atlantic Ocean and the North Sea, both having frequent development of low pressure systems and associated storm surge effects, which were incremented by spring tides coincidence in a system with a complex tide regime and southwesterly winds. The less relevance of flood triggers supported by the lack of rainfall, fluvial discharge and insufficient urban drainage is corroborated by other studies regarding Solent flooding (Ruocco *et al*., 2011; Wadey *et al*., 2012).

The Tagus Estuary flood event (November 1997) exhibited a combination of four forcing factors. Rainfall and fluvial discharge reflect both the estuary geographic position relative to the Atlantic Ocean and the Tagus basin influence. High tides coincidence and insufficient urban drainage are linked with estuarine dynamics and widespread urban occupation along the estuarine margins. The relevance of these forcing factors in Tagus Estuary flooding were corroborated by others studies (Cardoso *et al*., 2015; Rilo *et al*., 2017) and draw attention to the influence of Tagus River discharges and to the coincidence of heavy precipitation events with high tide and a deficient urban drainage system in estuary flooding .

Despite the above mentioned differences on the flood triggers, the damage analysis displays a similar typology record across systems (Figure 3) which means that for different territorial contexts and events, the damages typology is quite similar showing a consistent pattern. The exception is the institutional involvement lacking in the Solent estuary records that might be associated with the sources limitations.

The study reveals that for a less urban estuary such as the Shannon damages typologies are consistent with the other two estuarine systems that have a dense urban fabric and human occupation. Furthermore, it also highlights that events with different combinations of flood triggers have a similar damage typology record. Overall the analysis points out that estuarine flood triggers are system dependent other than damages typologies that present similarities between different systems.

Damage records consistency between systems allows the comparison and establishment of two distinct categories of damage typologies dependent on their relevance and impact that are associated with two management levels (Figure 4).

The first category comprises infrastructure, economic and human damages and is related with a strategic management level since it represents a set of damages that need a long-term response involving from land use planning to policy learning practices. The second category includes circulation interruption and functions disruption and is related with an operational management level since it embodies short-term response situations requiring preparedness of local authorities to respond.

This type of framework is useful for management authorities, since they usually use historical data to validate options and models, supporting warning and alert system response along with defense infrastructures capability.

## CONCLUSIONS

The study compared three distinct flood events in three estuarine systems located in Western Europe, selected based on a set of criteria from previous estuarine flood damage databases. The comparison highlighted that flood event triggers are dependent on the estuarine system and in contrast pointed out the similarities of flood damage records independent on the estuarine system. The damage record consistency allowed the establishment of a common damage typology corresponding to two management levels.

In summary, the study presented a conceptual framework for damages independent of the estuarine system and highlights the limitations to obtain a framework for triggers. Nevertheless this study also point to the necessity of further research on estuarine flood damages categorization. Future work should include a large set of events preferably obtained in other estuarine systems to confirm, and enlarge the damage categories.

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