The effect of storm events in the Tagus estuarine margins

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Abstract: Floods in estuaries can be forced by factors associated to ocean and inland sources. In the particular case of the Tagus estuary, the water level variability is mostly driven by tides and storm surges. One of the most recent flood events with the greatest impact in this estuary occurred on February 2010 associated with the passage of the Xynthia storm by the Portuguese coast. In the present study this flood event and related impacts are characterized considering two different territorial contexts: urbanised and productive agricultural areas. The territorial characterization of the potential flooding areas for a similar event considering a sea level rise scenario, obtained through numerical modelling, shows important contrasts in flooding extensions and in the exposed elements typology. These results are relevant for flood risk management, contributing to the definition of adaptation measures to improve the capability to cope with future extreme events.

Key words: Storm surge, flood, estuaries, sea level rise, territorial context.

1. INTRODUCTION

The projected rates of global sea level rise increase the attention on the potential for flooding events in estuaries (Bilskie *et al.,* 2014). The human and physical impacts that recent events had in estuarine areas (e.g. the hurricane Sandy (2012) in New York, Aerts *et al.,* 2013), show the need to improve tools that can support emergency and land-use planning. Past flood events give a wealth of information that can be used to better understand the flooding process and its forcing mechanisms, and to validate predicting tools that can support the development of management strategies.

The Tagus estuary, located in the Portuguese west coast (Fig. 1), is one of the largest estuaries in Europe and the Portuguese most relevant estuary due to its social and economic context and environmental characteristics. Included in the Metropolitan Area of Lisbon, the estuarine water front presents strong territorial contrasts (Tavares *et al.,* 2015). The particular morphology of the estuary affects the spatial variation of the extreme water levels along the estuarine margins, and the water elevations are mainly dominated by tides and storm surges (Fortunato *et al.,* 1999, Vargas *et al.,* 2008, Guerreiro *et al.,* 2015). The conjugation of storm surge conditions and extreme high tidal levels can lead to estuarine margins flood episodes such as the one that occurred on February 15, 1941, with high human casualties and property damages (Freitas and Dias, 2013). A regional geodatabase of historical flood occurrences in the Tagus estuary indicates that the probability of occurrence of one or more flood events in one year is 26% (Rilo *et al.,* 2015). The same authors point out that these occurrences are broadly distributed along the estuarine margins between Vila Franca de Xira and Oeiras (Fig. 1). The most recent flood event with the greatest impact along both margins occurred on February 27, 2010 associated with the Xynthia storm which had impressive and tragic effects in the southwestern coast of France (André *et al.*, 2013). The storm was originated in a low-pressure zone, located in the middle of the Atlantic Ocean, which intensified in the morning of the February 27 and changed to a storm when the coastlines of Portugal and Spain where reached (Bertin, *et al.*, 2014).

Fig. 1. Study areas in the Tagus estuary (Seixal old city centre and Lezíria Grande de Vila Franca de Xira). Location of: Cascais tidal gauge and Lisboa Geofísico meteorological station.

In this paper the impacts of this storm on the estuarine margins are characterized considering two territorial contexts: urbanised (Seixal old city centre - SOCC) and productive agricultural areas (Lezíria

Grande de Vila Franca de Xira – LGVFX). Also, the potential impacts of a similar event occurrence considering a sea level rise scenario are discussed.

2. METHODS

The potential water levels forcings in the estuary were analysed based on: water level and atmospheric pressure at the Cascais tidal gauge (see Fig. 1 for locations); atmospheric pressure, wind and precipitation at the Lisboa Geofísico meteorological station; daily average discharge from the Almourol hydrometric station (75 km upstream Vila Franca de Xira); harmonic synthesis based on a regional tidal model (Fortunato *et al.,* 2016). The characterization of the event's associated impacts is based on the regional geodatabase of historical flood occurrences (Rilo *et al.*, 2015) and other available data for the study areas. The extension of the flooded and damaged areas was reconstructed using a RTK-DGPS, complemented with other information.

Territorial vulnerability (TV) was assessed at the statistical block level based on the statistical procedure followed in the Social Vulnerability Index (Cutter *et al.*, 2003), which application in the Tagus estuary is thoroughly presented in Tavares *et al.* (2015). A single metric for TV and its 8 principal components (FAC's) that characterize the main drivers of vulnerability in the study area were calculated. The LGVFX area (Fig. 1 and 3) is comprised by a single statistical block while the SOCC area (Figure 2) is comprised by 3 statistical blocks (1, 3 and 4) (Table I). From north to south, SOCC-1 covers the Seixal fluvial station and a new residential area, block SOCC-4 includes the majority of the old city center, and finally, SOCC-3 includes the southern part of the SOCC, an old industrial facility (Mundet) and new urban area that includes the city hall and the cultural centre.

Water levels were simulated with the coupled circulation-wave model SCHISM (Roland *et al.,* 2012). The model domain extends from Santarém (about 40 km upstream Vila Fanca de Xira) to the coast and has a resolution of tens of meters along the margins. It is forced by results from an atmospheric model (Liberato *et al.,* 2013), a regional wave model (Fortunato *et al.,* submitted) and a regional tide and surge model (Fortunato *et al.,* 2016a). Details on the model application and validation are provided in a companion paper (Fortunato *et al.,* 2016b). The water levels were simulated for two different conditions: the same oceanographic and atmospheric forcings of the 2010 event and considering 0.5 m of mean sea level rise (SLR).

The expose elements of the potentially affected areas were analysed using land use/land cover (LULC) data from the Portuguese Land Use Chart of 2007 (COS'07) at the maximum level of disaggregation (level 5).

3. STUDY AREAS

The SOOC is located in the southern margin of the Tagus estuary, in a waterfront within a small bay (Seixal bay) sheltered from the estuary by a 2.3 km long sand spit (Freire *et al.,* 2013) (Fig. 1). The LGVFX is a productive agricultural area that covers about 130 km^2, located in the eastern margin of the estuary (Fig. 1). Separated from the estuary by walls and dykes, the land is below the present mean sea level. Flooding episodes of both oceanic and fluvial origins are frequent.

Both study areas differ significantly in terms of vulnerability components and final composite TV (Table I). The main driver of TV in the LGVFX area is the educational level (FAC7). This rural area presents very low vulnerability in FAC2 (residential areas of families with care-giving responsibilities) and FAC5 (building size). In the urban area, the remaining principal components – FAC1 (old neighbourhoods and population with constraints), FAC3 (residential areas of population with high economic status), FAC4 (population mobility), FAC6 (old urban areas with an aged population) and FAC8 (urban development) – are unevenly classified through the blocks that comprise the SOCC. Mobility (FAC4) is more critical in the block where the fluvial station is located as residents are more dependent on this transport in comparison to the other blocks. In general, the rural context (LGVFX) presents lower vulnerability than the urban context (SOCC).

Table I. Vulnerability classification at the statistical block in the study areas.

Study areas		Principal components (FAC) of TV								TV
		1	2	3	4	5	6	7	8	
LGVFX		L	VL	L	L	VL	M	H	L	VL
SOCC	1	H	M	L	H	L	L	L	L	L
	3	H	M	H	M	VL	M	L	L	M
	4	M	M	M	M	VL	M	H	VH	H

TV (territorial vulnerability) legend: VL-very low; L-low; M-moderate; H-high; VH-very high. SOCC-1, SOCC-2 and SOCC-3 represent the 3 statistical blocks that cover the SOCC area.

4. FLOOD EVENT OF FEBRUARY 2010

4.1. Event characterization

The analysis of the potential oceanographic and atmospheric forcings of the estuarine water levels during the February 27, 2010 event show that a combination of different factors occurred: high spring tide (4.22 m, above chart datum - CD, maximum water level registered in Cascais), storm surge conditions (0.52 m, surge in Cascais based on harmonic synthesis and tidal gauge data at Cascais; 976.2 hPa, minimum atmospheric pressure registered in Lisbon) and very strong local winds (98 km/h, maximum wind intensity from SW in Lisbon). The consequences of this event could have been worse if the storm surge had occurred during the maximum height of the spring tide on March 2 (4.29 m CD, maximum water level registered in

Cascais). As stated before, regarding the estuary, the Tagus river discharge only has impact on the maximum water levels in the upstream sector. The daily average discharge in the Almourol hydrometric station during the studied event (3332.6 m^3/s) is below the 5-year return period value (Management Plan of River Tagus Region).

Due to margins overtopping and flooding the event promoted important physical losses along the estuarine margins. The damages occurred in the waterfront of five municipalities in the Lisbon metropolitan area (Lisboa, Oeiras, Seixal, Alcochete and Vila Franca de Xira, Fig. 1). Considerable damages were registered, namely in the Lisbon Port facilities and public infrastructures such as marginal sidewalks, pavements and public seats. Traffic was interrupted at one of the most touristic places in Lisbon (Ribeira das Naus).

4.2. Local impacts

The Seixal waterfront was one of the most affected areas (Fig. 2), in particular the old city centre. In the SOCC a total of 30 houses were flooded, including private homes and commercial buildings, and the traffic on public roads was interrupted.

Fig. 2. February 2010 flooding event in SOOC: reconstruction of the flood extension (red patch); model results for the 2010 event (light blue) with SLR (dark blue) (image: ESRI Aerial Imagery).

The physical impacts also included extensive damages in basements and road infrastructures, and the societal impacts result mainly from traffic and services disruption. The event mobilized local authorities namely Seixal municipality services and civil protection services, police and the fire-fighters department. Besides the February 27 episode, the SOOC suffered a second flood episode on March 2 associated to the maximum spring water level (see above). Flooding episodes in this area can also occur without overtopping only by the water inflow into the urban drainage system (during extreme high water levels) and its overflow through sinks. In this situation flooding is aggravated by intense precipitation. In the LGVFX the storm surge event promoted damages in the dykes and overtopping in some places leading to agriculture land flooding (Fig. 3). As this event occurred out of the active farm season only up to 5 families and some cattle were evacuated. Other impacts in the upstream area of the estuary included the interruption during one hour of the main railway line and the evacuation of one person from the Mouchão de Alhandra where the rupture of the dyke in the southern area occurred (Fig. 3).

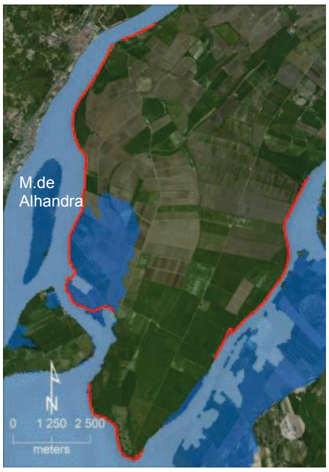

Fig. 3. February 2010 flooding event in LGVFX: reconstruction of the flood affected area (red line); model results for the 2010 event (light blue) with SLR (dark blue) (image: ESRI Aerial Imagery).

5. CHARACTERIZATION OF POTENTIALLY AFFECTED AREAS

The potential affected areas by an event with Xynthia characteristics and SLR will increase in 1.87 hm^2 and 616.03 hm^2 in SOOC and LGVFX, respectively (Fig. 3 and 4, Table II). The largest increase in the latter is due to the low topography, mainly below the present mean sea level.

Table II. LULC classes flooded in the event of 2010 with and without SLR in the study areas.

	Flooded area							
	SOCC				LGVFX			
	Without SLR		With SLR		Without SLR		With SLR	
LULC	hm^2	%	hm^2	%	hm^2	%	hm^2	%
U	1.77	20.4	3.20	30.3	0.00	0.00	0.00	0.00
P	3.62	41.7	3.83	36,3	0,00	0,0	0,00	0,0
I	0.34	3.9	0.34	3.3	0.00	0.0	0.00	0.0
FF	0.00	0.0	0.00	0.0	0.41	0.5	1.68	0.2
RN	0.00	0.0	0.00	0.0	2.33	3.1	5.12	0.7
G	1.29	14.9	1.34	12.7	0.00	0.0	0.00	0.0
IC	0.00	0.0	0.00	0.0	40.10	52.8	638.8	92.3
Sd	0.01	0.1	0.19	1.8	0.00	0.0	0.00	0.0
S	0.64	7.4	0.64	6.1	0.01	0.0	0.01	0.0
BD	0.96	11.1	0.96	9.1	0.00	0.0	0.00	0.0
WL	0.00	0.0	0.00	0.0	18.71	24.7	28.12	4.1
NC	0.00	0.0	0.00	0.0	14.31	18.9	14.46	2.1
AC	0.00	0.0	0.00	0.0	0.00	0.0	3.77	0.6
FD	0.04	0.5	0.04	0.4	0.00	0.0	0.00	0.0
Total	8.67	100.0	10.54	100.0	75.87	100.0	691.9	100.0

LULC legend: U - Urban (continuous and predominantly horizontal); P - Parking areas; I - Industry; FF - Farmland facilities; RN - Road network; G - Gardens; IC -Irrigated crops; Sd - Shrub (dense); S – Shrub; BD - Beaches, and dunes; WL – Wetlands; NC - Natural watercourses; AC - Artificial watercourses; FD - Fluvial docks.

The potentially affected areas in the two scenarios (without and with SLR) show significant differences in the expose element typologies (Table II). In the SOCC the most represented typology is parking areas (41.7% in the scenario without SLR and 36.3% with SLR) and urban areas (20.4% of total flooded areas in the scenario without SLR and 30.3% with SLR). Green areas (mostly public gardens) and beaches and dunes also present significant flooded areas. In the LGVFX the most affected typologies of LULC in the flood event of 2010 were the irrigated crops (52.8% of total affected area). In a scenario of SLR, the 2010 event would affect a significantly greater irrigated area (638.8 hm^2), representing 92.3% of total affected area. Wetlands and natural water courses are LULC types also greatly affected by flooding in both scenarios in the LGVFX.

6. CONCLUSIONS

Storm surge episodes associated with high spring tides can force overtopping and flooding in the Tagus estuary margins, as observed during the Xynthia storm event. During this event important physical losses were registered along the estuarine waterfront, societal impacts resulted mainly from traffic and services disruption, and in a specific case people had to be evacuated. The potential flooding areas considering a similar event and a sea level rise scenario, in two different estuarine contexts (urbanised and agricultural areas), show a relevant increase in the flood extension and contrasts in the exposed elements typology. These results can contribute to the definition of flood risk management strategies as emergency and land-use planning.

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