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ORIGINAL PAPER

A local-scale approach to estuarine flood risk management

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Abstract New challenges in flood risk management are raised by climate change and land-use development. These challenges are particularly complex in estuarine and coastal systems, where different hazard sources interact in a dynamic socio-economic context. This paper presents an innovative approach to support flood risk management in estuaries. The approach, developed at a local-scale basis, is applied in the case study of the Tagus estuary (Portugal). The methodology is supported by the regional framing of the study area and integrates hazard, exposed elements, territorial vulnerability and risk assessments

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considering different climate scenarios. Through the involvement of the various risk management dimensions, the results allow the definition of a new decision-making supporting framework for emergency and land-use planning. At the emergency level, the results include a WebGIS interface providing an early warning system for the locations with highest risk of flooding and the definition of emergency planning guidelines. A set of flood adaptation actions based on land-use and occupation measures are recommended to increase resilience in face of flooding and future sea level rise. The institutional capacity-building is achieved through the availability of information and tools that can effectively support decision-making. Additionally, the outcomes contribute to better understand flood risk in estuaries and to strengthen its prevention, preparedness and response, priorities defined in the Sendai Framework for Disaster Risk Reduction 2015–2030.

Keywords Flooding · Estuaries · Territorial vulnerability · Extreme events · Early warning · Decision-making

1 Introduction

Floods can have devastating consequences on the economy, environment and people with high associated costs. In Europe, it is reported that between 1998 and 2009, flooding and storms were the most costly hazards, with 1126 fatalities and the displacement of about half a million people, with overall losses associated with floods of €52 billion (EEA 2010). More recently, the floods of June 2013 led to an estimated €12 billion in economic losses across nine EU Member States (EC 2014). Flood drivers and impacts will be affected by future climate change in combination with land-use changes and water management practices (Simonović 2012). The observed extreme flood losses in Europe are expected to more than double in frequency by 2050 under future climate change and socio-economic development (Jongman et al. 2014). Over the last decades, flood management policy has shifted from providing flood hazard protection measures towards a more adaptive and integrated flood risk management approach (Ward et al. 2013; Kousky and Shabman 2015). Aiming to reduce the adverse consequences of flood risk in a climate change context, the EU Floods Directive (Directive 2007/60/EC) creates a common framework to establish flood areas, flood risk maps and flood risk management plans. Management plans should focus on prevention, protection and preparedness, including flood forecasts and

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early warning systems, and the promotion of sustainable land-use and water management practices. Nevertheless, few studies address adaptive and integrated systems of flood risk management at a city level (Ward et al. 2013).

Estuaries are among the coastal systems where the flood risk is highest, due especially to the extensive occupation of adjacent low-lying areas, which host about 70 % of the largest cities in the world (Morris et al. 2013). This risk is likely to increase with climate change effects, such as sea level rise (IPCC 2014), and the people and economic assets located on its margins keep increasing. The social and physical impacts of recent events, such as in 2005 the hurricane Katrina in New Orleans (Miller et al. 2015), in 2010 the storm Xynthia along the French coast (Bertin et al. 2014; André et al. 2013) and in 2012 the hurricane Sandy in New York (Aerts et al. 2013), draw attention to the need to improve risk management in those systems. Risk assessment and management in estuaries raises several challenges related to the interaction of different hazard sources, such as tides, river flows, wind and waves, and the socio-economically dynamic nature of these systems. This complexity requires multi-level approaches, implying a multi-scale assessment of the existing conditions to address specific information demands (Santos et al. 2015).

This paper aims at presenting an integrated approach to support flood risk management in transitional systems taking into account different levels of the decision-making process, emergency and land-use and occupation planning considering different climate scenarios. This approach is applied at a local scale, identified in previous studies through the hazard, exposure and territorial vulnerability assessments at a regional scale (Tavares et al. 2015; Freire et al. 2015).

The study area, the municipality of Seixal, is located in the southern margin of the Tagus estuary (Portugal) (Fig. 1) and is one of 11 municipalities of the Metropolitan Area

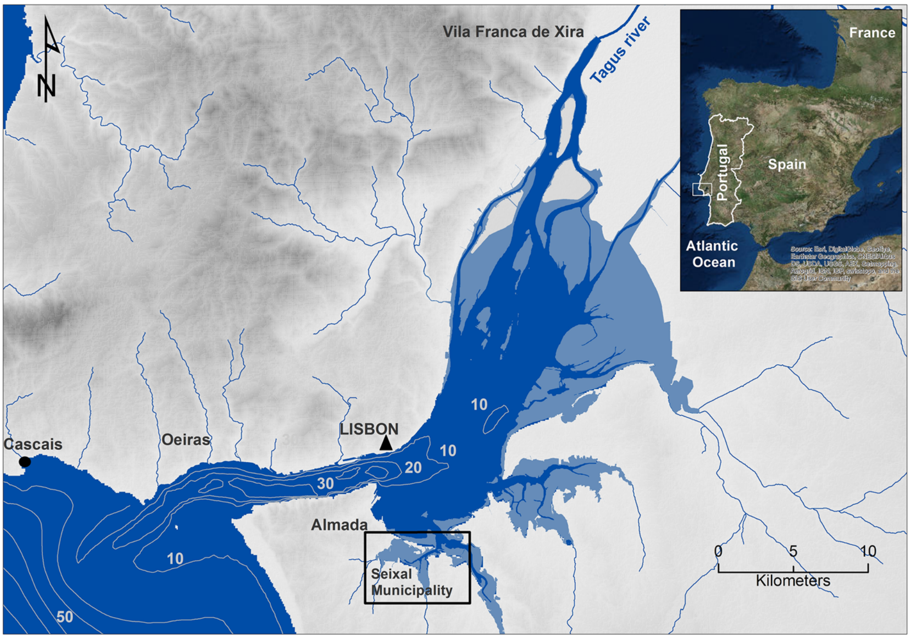

Fig. 1 Location of the study area in the Tagus estuary. Location of monitoring stations mentioned in the text: Cascais tidal gauge (*circle*) and Lisboa Geofísico meteorological station (*triangle*)

of Lisbon that constitute the estuarine marginal area. About 1.6 million of inhabitants, mostly concentrated in the western and northern sides, live along the estuary margins (Tavares et al. 2015). The waterfront of the Seixal Municipality was particularly affected by past floods, showing specific territorial vulnerability characteristics. Local and regional planning instruments are now required to incorporate risk mapping and more detailed characterization of flood-prone areas, partially as a consequence of the transposition of the Floods Directive to the national law. Being recent changes, the experience in their implementation and influence over management decisions at the local level is still limited. Nevertheless, a few recently revised Portuguese municipal land-use plans, such as those of Lisbon, Coimbra and Seixal, already include detailed flood risk maps. These plans come at a time when municipalities are being strongly encouraged by regional planning commissions towards the definition of conservative expansion areas for urban centres, in stark contrast to the very optimistic urban perimeters of only a decade ago.

The paper is organized as follows. In Sect. 2, the framework of the study area in the Tagus estuary context is presented, addressing the historical past flood events, the hazard sources (extreme water levels) and the territorial vulnerability. The flood risk management approach followed in the present study is described in Sect. 3. In Sect. 4, the results of the hazard, exposed elements, vulnerability and risk assessment for the study area are presented. Based on these results, a decision-making supporting framework is presented and discussed in the following section, at both emergency and land-use planning levels. Finally, the conclusions are addressed in Sect. 6.

2 Framing the study area in the Tagus estuary context

2.1 Historical flood events

A previous study, based on a regional database (r_DB) of historical flood occurrences (Rilo et al. 2015), revealed that the probability of occurrence of one or more flood events in the Tagus estuarine margins in one year is 26 %. These authors defined an "occurrence" as a geographically defined place affected by estuarine flooding, independently of its severity, which is described or appears in selected data sources; the occurrences can be grouped into a single event following a temporal criterion. Based on Rilo et al.'s (2015) results and updated data in the present paper, 235 occurrences were registered along the estuary margins between 1865 and 2013, related to 45 flood events. These flood occurrences are widely distributed along the margins between Vila Franca de Xira (the downstream limit of freshwater floods) and Oeiras (at the sea entrance), with high incidence on the Lisbon and Oeiras municipalities (Fig. 1). The maximum number of events recorded in one year was three, in 1936 (Fig. 2), and the years with the largest numbers of occurrences were 1945 (25), 1937 (24), 1941 and 2010 (15 each).

The frequency of the historical flood occurrences analysed is higher between 1930 and 1950, showing a decrease thereafter (Fig. 2). That period overlaps intense rainy years, during which severe urban inundations were registered (Oliveira and Ramos 2002). Between 1950 and 1970, the Tagus hydrological regime suffered major changes due to the construction of more than 140 dams in the river basin; after 1970, the flow regime of the Tagus river in Portugal depends mostly on the operation of the Alcântara dam in Spain, and a clear downward trend in the maximum flood flow and flood frequency is observed (ARH do Tejo 2011).

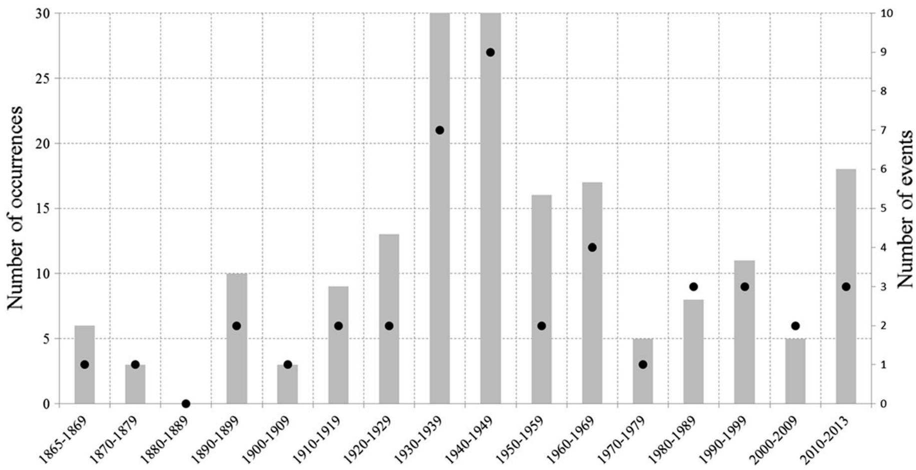

Fig. 2 Temporal distribution of decadal flood occurrences and events between 1865 and 2013. The *circles* represent the number of events for each period *Source*: Information in Rilo et al. (2015)

Different triggering factors contribute to flood occurrences along the Tagus estuarine margins. In the narrow upstream sector of the estuary, the river flow can have an important effect on water elevations. Elsewhere, the estuary cross-sectional area increases significantly and the water elevations are dominated by tides and storm surges (Vargas et al. 2008; Guerreiro et al. 2015).

In adjacent urban areas, high levels of estuarine waters can affect the drainage capacity of sewer systems, particularly during episodes of intense and concentrated in time rainfall (David et al. 2015). The past flood events are associated with multiple causes in the historical sources: periods of intense rainfall (95 % of total events), high fluvial discharge (80 %), deficient urban drainage (70 %), severe wave conditions (45 %), low atmospheric pressure events (41 %) and high tidal levels (34 %). The results based on historical information must be carefully assessed, as mentioned in previous studies (Barriendos et al. 2006; Santos et al. 2014), taking into account the reliability of the information sources (depending on the type of sources, variations of journalistic criteria through time) and of the database itself (depending on the inclusion criteria, availability of sources and temporal period covered by the database).

Due to their wide spatial effects and associated impacts, two historical flood events in Tagus estuary emerge from the available information previous described (Table 1): 15 February 1941 and 27 February 2010. The former is mentioned in the literature as the biggest catastrophe that occurred in the Iberian Peninsula in the last 200 years, causing high human casualties, extensive infrastructural damages and services disruption along the Portuguese coast (Muir-Wood 2011; Freitas and Dias 2013). Strong wave action driven by south-westerly winds combined with a major storm surge caused severe damages in houses and infrastructures along the Tagus estuarine margins between the estuary mouth and Vila Franca de Xira and the sinking of 150 boats close to Lisbon (Muir-Wood 2011). The resulting human losses registered include 28 casualties, 14 wounded, 125 evacuees and 3 displaced (Freire et al. 2015). The February 2010 flooding episode was associated with the Xynthia storm whose tragic effects in the western coast of France are well documented (André et al. 2013). In the Tagus estuary, this storm, which followed a similar trajectory as the one that occurred in 1941 (Breilh et al. 2014), affected both margins between Oeiras

Table 1 Potential forcing factors of maximum water levels (see Fig. 1 for locations)

Event	Tidal range (m)[a]	Min. atmospheric pressure (hPa)	Inverted barometer effect (m)[d]	Maximum surge level (m)[e]	Max. wind intensity (km/h)/ direction (azimuth degrees)[b]
15 February 1941	3.17	952.1[b]	0.63	–	129/270
27 February 2010	3.02	976.2[b] 986.0[c]	0.39 0.29	0.64	98/202

[a] Harmonic synthesis based on the regional tidal model of Fortunato et al. (2016)

[b] Data from Lisboa Geofísico meteorological station

[c] Data from Cascais tidal gauge (ftp://igeo.pt/Cascais/maregrafo/) for the 2010 event. No data available for 1941

[d] Based on atmospheric pressure data (2 and 3)

[e] Calculated based on harmonic synthesis and Cascais tidal gauge data

and Vila Franca de Xira. Although without human losses, considerable damages in infrastructures were recorded at the estuarine waterfront including the Port of Lisbon facilities, located in the northern margin. One of the areas most affected by this event was the Seixal waterfront (Fig. 1) where the flood impacted private homes and commercial buildings and disrupted the traffic on public roads in the historical district. The analysis of the potential water levels forcings in the estuary (tide, atmospheric pressure, wind and Tagus river discharge) during the two historical events shows that flooding levels in both events are associated with the combination of spring tide, storm surge conditions (above 0.60 m) and very strong local winds (maximum intensity in Lisbon of about 130 km/h in 1941 and wind gusts over 100 km/h in 2010) (Table 1).

2.2 Extreme water levels

Water levels in estuaries depend on several meteorological and astronomic forcing agents: tides, wind, atmospheric pressure, river flow and waves. However, the relative importance of the different forcing agents varies widely across and within estuaries. In the particular case of the Tagus estuary, the variability of the water level is mostly due to tides. Tidal ranges at the coast (Cascais) vary between 0.55 and 3.86 m (Guerreiro et al. 2015). Inside the estuary, these tidal ranges are further amplified by resonance, which selectively amplifies semi-diurnal constituents (Fortunato et al. 1999). Storm surges can also contribute significantly to the water level. Andrade et al. (2006) estimated storm surges of 46–58 cm at Cascais, for return periods of 5 and 100 years, respectively. In contrast, the effect of river flow on water levels is limited to the upper reaches of the estuary, about 40 km upstream of the mouth (Vargas et al. 2008).

The water levels in the estuary, for a return period of 100 years and present mean sea level (MSL), vary from about 4.5 m (CD chart datum: 2.08 m below MSL) at the estuary mouth to 5.1 m (CD) at its head (Fig. 3). Several marginal areas are inundated, including the Seixal area and its surroundings.

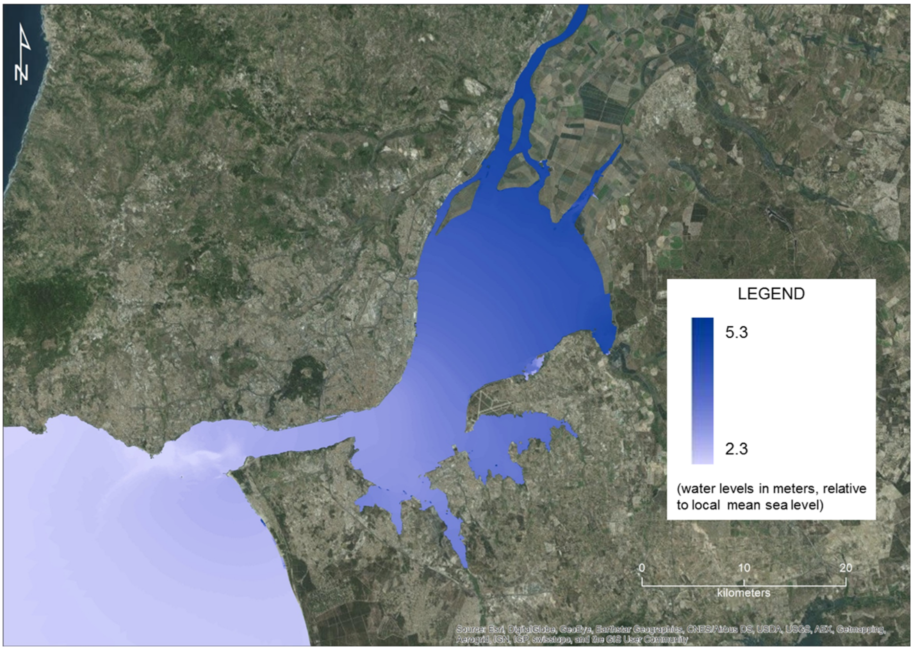

Fig. 3 Extreme water levels in the Tagus estuary for a return period of 100 years. This map was generated by forcing a circulation model of the estuary with a time series of elevations produced by a statistical analysis of tide gauge data from Cascais. The method is described in Fortunato et al. (2013) and its application to the Tagus estuary in Guerreiro et al. (2015). The application and validation of the circulation model is presented in Fortunato et al. (2015). See Sect. 3.2 for further details

2.3 Territorial vulnerability

The knowledge of the vulnerability of a given territory has several applications in risk management. It is a concept closely related to resilience, quantifying a community's capacity to adapt and recover from disasters (Cutter et al. 2008; Bergstrand et al. 2015). Applications can be identified according to the selected geographical scale of analysis: nationwide assessments produce knowledge from a global risk governance perspective (Angeon and Bates 2015), while local applications are useful, for example, in emergency and spatial planning at the municipal level (Guillard-Gonçalves et al. 2014; Perrow 2006, 2007).

In the present study, the assessment of territorial vulnerability contributes to a wider framing of the Tagus estuary regarding its socio-economic, demographic and urban characteristics and dynamics. Additionally, such assessment contributes to the identification of vulnerability drivers and a detailed knowledge on the location of the most vulnerable risk groups (Cutter et al. 2003; IPCC 2014). A territorial vulnerability assessment methodology was applied to the Tagus estuary area (Tavares et al. 2015) over a set of 1147 statistical blocks located along the estuarine margins, in order to consider both directly and indirectly affected areas. The assessment identified old buildings and neighbourhoods, aged population, unemployment, care-giving responsibilities, educational level, commutation dependency and urban density as the main vulnerability drivers, exemplified by the areas numbered 2, 4 and 5 in Fig. 4. In contrast, in the areas numbered 1, 3 and 6, statistical

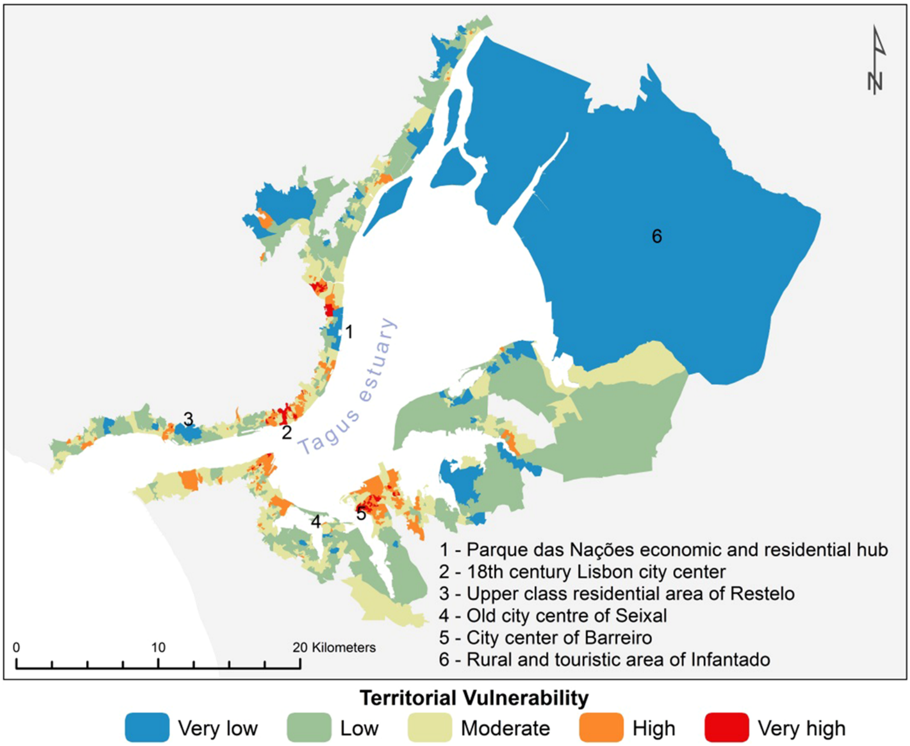

Fig. 4 Territorial vulnerability in the Tagus estuary

blocks characterized by high percentage of individuals and families with high educational level and economic status and low rate of unemployment present a low social vulnerability.

2.4 Seixal waterfront characterization

The waterfront of the Seixal Municipality is located in the southern margin of the Tagus estuary (Fig. 5) and is the local study area of this work. The downscale of analysis from the estuary level to this municipality requires specific strategies of flood risk management and, therefore, specific methods of risk assessment.

The waterfront of the Seixal Municipality is comprised of three parishes—parish of Seixal, Arrentela and Aldeia de Paio Pires, parish of Amora and parish of Corroios—which are the local administrative and political organizational level. They all present a very similar number of residents (44 920, 48 629 and 47 661, respectively). Nevertheless, the area closer to the waterfront—a buffer with a length of 1000 m considered in the territorial vulnerability assessment—registers, in those three parishes, a total of 92,004 inhabitants, representing 65.2 % of the total resident population. Hence, a significant proportion of each parish's population resides near the shoreline. The waterfront has different typologies of urban occupation, from a consolidated old city centre to more dispersed urban areas that grew over time. The land-use in non-urban areas is composed of natural and wetland areas, aquaculture, active and inactive naval shipyards, abandoned industrial areas and

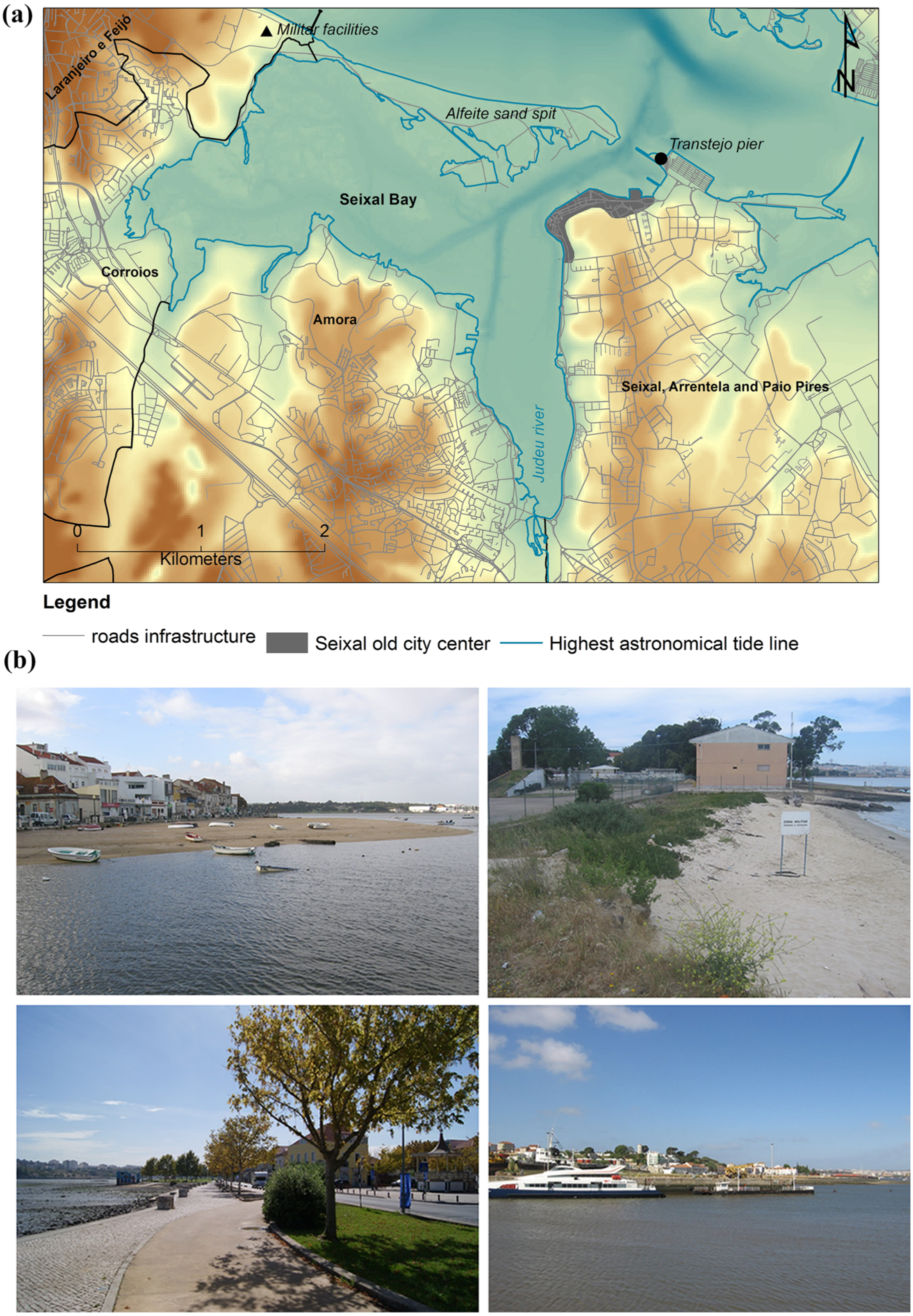

Fig. 5 **a** Seixal waterfront showing *block* statistical-level division, **b** Four different aspects of Seixal waterfront territory. Digital terrain model based on: topographic information from the Military Chart (1/25000 scale) from the Centro de Informação Geoespacial do Exército (CIGeoE), topographic data from the Agência Portuguesa do Ambiente (APA) and bathymetric data provided by the Seixal Municipality

recreational areas. The municipality's most relevant critical infrastructure is the road and fluvial interface which provides transportation between the two margins of the estuary.

In terms of hydrological features, the Seixal waterfront is configured by a small bay (about 480 ha in area) in which a tidal channel system nourishes silty-mud flats and salt marshes (Fig. 5). The bay is sheltered from the direct influence of the estuary by a 2.3-km-long sand spit with an active beach anchored in the northern side (Alfeite beach), one of the longest beaches in the estuary (Freire et al. 2013). The channel of the Judeu river connects the interior of the bay with the estuary. Due to its natural resources and sheltered conditions, this area has long attracted human activities mainly associated with fishery and shipbuilding, hosting also harbour and military facilities. These natural characteristics make the Seixal waterfront widely used by the local population for recreational activities, such as nautical activities and bird watching, justifying a municipal investment in marginal facilities for jogging and cycling, along with an eco-museum at an old water mill.

3 Methodological approach

3.1 General approach

Adequate flood risk management measures in transitional systems should be sustained by validated risk assessment methodologies that integrate the diversity of hazard sources. Herein, a risk management strategy is proposed that aims at providing a scientific and information-based support to enhanced flood risk management measures. This risk management approach is schematically presented in Fig. 6 and is split into two major sections: risk management and decision-making.

3.2 Risk assessment

Information on past flood events contributes to improving the knowledge about flood drivers, flood characteristics and associated impacts. Historical flood records for the Seixal

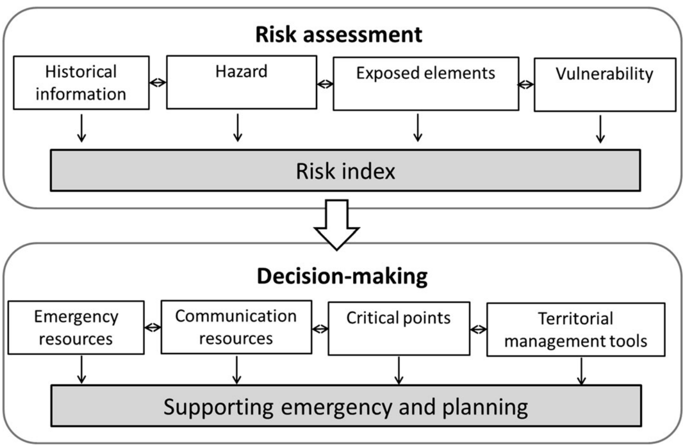

Fig. 6 Risk management approach scheme followed in the present study

Municipality were assessed through the compilation of two local databases of flood occurrences maintained by the local emergency authorities: the Seixal fire department and the Seixal Municipal Service for Civil Protection (SMPCS). Those two databases were analysed and compiled into a single local database (L_DB) structure to allow the integration of different types of data. Since the objective was to capture the estuarine influence on floods, only the occurrences related to flood events of natural origin and geographically located below 20 m (MSL) were considered. The L_DB is structured in four groups of information: basic data regarding date and location, flood impacts (e.g. casualties, damages), flood characteristics (e.g. flood extension, depth) and flood-triggering factors (e.g. rainfall, fluvial discharge, tides).

In the scope of the characterization of past events, the maximum extension of flooded area in Seixal old city centre in 2010 was reconstructed using a RTK-DGPS with the support of the Seixal Municipality services. The results were further complemented with photographs and other records acquired during the event. To complement the historical information, the flood extension and impacts and the water levels in the estuary were also acquired in situ during particular oceanographic and meteorological conditions that occurred in 2014 and 2015. All the acquired data provided crucial information for understanding the flooding process and hazard assessment validation.

Considering that the flood hazard at a given location depends on the hydrodynamic conditions, its assessment was based on the hazard index defined by DEFRA (2006):

$$I_h = H(U + 0.5) \tag{1}$$

where H (in m) is the total water depth and U (in m/s) is the depth-averaged velocity. Four classes of increasing hazard are defined based on the value of I_{h} (Table 2).

The spatial and temporal evolution of the total water depth and the depth-averaged velocity was determined using the circulation model SCHISM (Zhang et al. 2016). Derived from SELFE (Zhang and Baptista 2008), SCHISM is an open-source community-supported modelling system based on unstructured grids, designed for the seamless simulation of 3D baroclinic circulation across lake–river–estuary–shelf–ocean scales. Details on the application and validation of SCHISM in the Tagus estuary are provided in Fortunato et al. (2015). To construct the hazard maps, the model is forced at its ocean boundary by time series of elevations representative of conditions for selected return periods. These time series are generated through a statistical analysis of tide gauge data at the Cascais tide gauge, following the procedure described in Fortunato et al. (2013) and Guerreiro et al. (2015). The horizontal resolution of the model in the estuarine margins is of the order of a few tens of metres. While this resolution can be considered very fine, given the extent of the model, it is not sufficient to represent the building and other obstacles to the flow. The resistance caused by these subgrid-scale features on the flow is thus represented with added friction, based on the land cover. While this approach is adequate to determine the free surface elevation, it leads to the underprediction of the maximum velocities (Le Roy et al.

Table 2 Classes of the hazard index and description based on DEFRA (2006)

Hazard index	$I_h \leq 0.75$	$0.75 < I_h \leq 1.25$	$1.25 < I_h \leq 2.5$	$I_h > 2.5$
Degree of hazard	1—low	2—moderate	3—significant	4—extreme
Description	Caution	Dangerous for some	Dangerous for most people	Dangerous for all

2015). Therefore, the hazard also tends to be underpredicted in urban areas. The following three scenarios were considered: 100-year probability with a 1-m sea level rise (SLR), and 20- and 100-year probability without SLR.

The identification of exposed elements was based on geographic data obtained from various sources: the National Authority for Civil Protection (ANPC), the Municipal Service for Civil Protection (SMPCS) and those produced in previous projects made publicly available by Central Administration entities. The typology of exposed elements includes:

- Building implantation, road network and business/commercial points of interest;
- Critical infrastructures: civil protection, elderly population, childhood and education, leisure and sport, health, transportation, industrial areas, water supply and treatment;
- Cultural and architectural heritage;
- Land-use and land value: MorFeed Project land-use data (Rilo et al. 2013), Corine Land Cover 2012 data, property tax coefficient mapping;
- Environmental assets: stream network, notable trees, Urban Waste Water Directive sensitive zones, coastal ecosystems (MorFeed Project data).

The spatial representation of these elements was overlaid with the considered present and future estuarine flooding scenarios.

The vulnerability assessment considered the following typology of exposed elements: road network; buildings and environmental critical infrastructures; mobility (assessed through the presence of ATM machines, bus stops and transport hubs/interfaces); people's presence (assessed through the counting of circulating vehicles and parked vehicles through satellite imagery of the years 2007, 2011 and 2012). Following the assessment approach proposed by the Department for Environment, Food & Rural Affairs (DEFRA 2006), these elements define the area vulnerability (A_v).

Using the same approach of DEFRA, a value of people vulnerability (P_v) is taken from the assessment conducted at the estuary level, where the scores resulting from the principal component analysis (PCA) at each statistical block are used.

Table 3 presents the form in which input data are processed in order to calculate A_v and P_v. The product of A_v and P_v is the vulnerability index (I_v). I_v expresses therefore several dimensions of the vulnerability: those arising from the individual social characteristics, and those imposed by the territorial context both in terms of resident and transient population and in terms of activities. Rows from (*a*) to (*g*) and P_v identify raw input data. The mobility parameter (M_p) is the simple average of (*c*) and (*d*). The concentration areas parameter (Ca_p) is the simple average of (*e*) and (*f*). The range of values in the different parameters is highly variable, in accordance with the distinct nature and measure units in which they are expressed. For this reason, a linear transformation is performed using the minimum and maximum values in the parameters whose range is not initially between the interval [0, 1], in order to allow a direct calculus of A_v (Table 3).

Besides their representation as geographical entities (points, lines and areas), a vulnerability index (I_v) is evaluated by relating topologically these elements with the flood hazard index (I_h), which is expressed using a triangular network. This approach facilitates the calculus of the risk index because each triangle is assigned a hazard value as described above.

The risk index (I_r) is therefore the product of I_h and I_v in each triangle.

Table 3 Input data and processing for the evaluation of the vulnerability index

Input data		
Variables	Units	Scores
Road network density (*a*)	km/km^2	
Proportion of built areas (*b*)	%	
Vehicles' location (*c*)	Average of the number of vehicles in 3 different time frames	
Bus stop coverage (*d*)	Dimensionless	1—exact location, 0.5—adjacent location, 0—other locations[a]
ATM and bank coverage (*e*)		
Fluvial station (*f*)		
Environmental infrastructures (*g*)		
People vulnerability (P_v)	Dimensionless	Score of the territorial vulnerability assessment (between 0 and 1)
Intermediate parameters		
Mobility parameter (M_p)	$M_p = [(c) + (d)]/2$	
Concentration areas' parameter (Ca_p)	$Ca_p = [(e) + (f)]/2$	
Area vulnerability (A_v)	$A_v = [(a) + (b) + (M_p) + (Ca_p) + (g)]/5$	
Vulnerability index (I_v)	$I_v = A_v \cdot P_v$	

[a] In regard to the triangular network: score 1 if the geographical entity (bus stop, etc.) touches a given triangle; score 0.5 if a given triangle is adjacent to the triangle(s) touched by the geographical entity

3.3 Decision-making supporting tools

The developed approach focuses on two different dimensions of the decision-making support: (a) emergency planning and response to floods, based on a real-time forecast and early warning system communication framework; (b) territorial planning instruments based on potential flooding areas for different climate scenarios.

Two different emergency resources are available to support the decision-making strategy: the real-time data resources (Table 4) that provide the background data to the forecast and early warning system, and the emergency resources from the national and local civil protection services (Table 5).

3.3.1 Communication resources

An innovative real-time information system for enhanced support to flood risk emergency was developed to provide a gateway to all project data, from both emergency and risk analysis products. This information system was based on a customized deployment of the WIFF—Water Information Forecast Framework (Oliveira et al. 2014; Fortunato et al. 2015)—to address the specific requirements of flood risk management. The platform addresses several user requirements such as (1) fast, online access to relevant georeferenced information from wireless sensors, high-resolution forecasts and comprehensive risk analysis; and (2) the ability to adapt automatically and transparently to any device with data connection. Given its specific purpose, both data protection and tailored-to-purpose products are planned for through user-specific access roles.

Table 4 Real-time information resources

Resources	Provider	Description
Regional		
Atmospheric forecasting tools	NOAA (www.ncdc.noaa.gov)	Global forecast system wind and atmospheric pressure predictions
Oceanic forecasting tools	LNEC—National Laboratory for Civil Engineering (http://ariel.lnec.pt/)	Wave and sea level predictions
In situ monitoring sensors	IH—Hydrographic Institute through EMODnet (www.emodnet.eu/)	Sea level and mean wave parameters data
Local		
Atmospheric forecasting tools	Windguru (www.windguru.cz/)	Wind and atmospheric pressure predictions
In situ monitoring sensors	APA—Portuguese Environment Agency (snirh.pt)	River discharge data
In situ monitoring sensors	DGT—Directorate General for Territory (www.dgterritorio.pt)	Sea level data
In situ monitoring sensors	APL—The Port of Lisbon (www.portodelisboa.pt)	Sea level data

3.3.2 Critical points

The flood early warning system was implemented for selected critical points considering the risk assessment results and applying the following criteria:

- The early warning system should serve the areas directly affected by flooding classified with high and very high risk in the I_r;
- The early warning system should serve the areas directly affected by flooding classified with very low, low and moderate risk in the I_r, as long as they provide road or fluvial connectivity to areas—inside or outside the hazard areas—which would be significantly and indirectly affected by the disruption of such functions.

Four flooding warning levels were defined based on the forecast water height (H) (negative values correspond to situations in which the water surface at a nearby point is below the topographic height of the critical point) and the potential impacts.

- Level 1 (green)—$H < -0.20$ m: no warning, corresponds to the normal situation.
- Level 2 (yellow)—≤ -0.20 m $H < 0.20$ m: possible low flooding; the low-lying areas next to the water front may be flooded. Roads may be closed, and bicycle and pedestrian paths as well as some backyards of buildings may be affected.
- Level 3 (orange)—≤ 0.20 m $H < 0.50$ m: low to moderate flooding; in addition to the above, the flooded area is more substantial. Some buildings below the floor level may be affected.
- Level 4 (red)—$H \geq 0.50$ m: high flooding; in addition to the above, extensive areas are flooded. Many buildings may be affected below the floor level and some above the floor level.

Table 5 Civil protection resources

Provider	Resources	Description
National level		
ANPC	Human	The national authority of civil protection (Portuguese acronym ANPC) has the role of planning, coordinating and implementing the civil protection policy. It is also responsible for the civil protection resources, emergency planning and firefighters and maintains a central operational service
		The firefighters force (in Portuguese Força Especial de Bombeiros-FEB) is the branch of ANPC for disaster relief during emergencies, including floods and other adverse weather conditions hazards
		In terms of civil protection human resources, FEB effective scales to 280 persons adding other security forces, armed Forces, maritime and aeronautical authorities, National Institute for Medical Emergency and other health services
	Material	The FEB has currently 57 operational vehicles and 9 lighting balloons, 2 rescue vessels, 8 diving equipment, 10 aquatic rescue equipment, 12 rescue and extrication equipment, 1 rescue equipment in wide angle, 2 high-capacity generators, 16 medium-capacity generators, and 7 large inflatable tents
		An integrated emergency and security communication network (SIRESP) ensures the communications needs of the emergency forces and security services, allowing intercommunication and interoperability between those forces and services
Municipal level		
SMPCS	Human	1 Tactical team (2 members), 1 operational team (3 members) municipality backup human resources (1.600)
	Material	2 Tactical vehicles, specific emergency radio frequency and 20 radio devices, municipality backup resources (235 vehicles and construction equipment, 1 boat, about 1.000 warning and traffic signs)
Fire brigades	Human	280 (firefighters and rescue team members), 3 rescue teams, 1 diving brigade
	Material	54 vehicles, 3 boats, 21 ambulances, 18 rescue vehicles, 3 communication and command vehicles, 12 other vehicles for transportation and logistics

3.3.3 Territorial management tools

In recent decades, municipal land-use management and planning has been vastly improved through the implementation of mandatory municipal land-use plans (PDMs) and the introduction therein of several national, regional, and local theme maps and strategies. In their latest revision, they are now required to include risk maps, which highlight the territorial vulnerability associated with natural and technological hazards. Flood-prone areas are equally required to be transposed into zoning and building restrictions as part of the National Ecological Reserve. While this has been mandatory since 1990, the technical requirements and methods have been recently improved to reflect the transposition of the Floods Directive (Directive 2007/60/EC) into national law.

These changes, implemented ultimately at the municipal level, often derive from indications emanating from regional plans or national strategies. The Regional Land-Use Plan (PROT-AML) and the Estuary Management Plan (POET) are of particular interest to the Seixal waterfront and to the estuary as a whole. Both plans are pending final approval, but some of the measures therein are already being recommended by the Regional Coordinating Commission (CCDR) and the Portuguese Environmental Agency (APA), both central government agencies. Other sectoral plans, such as the Natura 2000 Plan, the Tagus River Basin Management Plan, or the Natural Reserve Management Plan, require incorporation into municipal planning, but their influence over local decision-making is less pronounced in the case of Seixal. Municipal emergency planning deserves a separate document (Seixal's latest Emergency Plan was approved in 2014 and is targeted mostly at emergency response and coordination among civil protection agents).

4 Risk assessment

4.1 Historical flood records

Historical flood records in the Seixal waterfront compiled in the L_DB comprise 48 occurrences between 2002 and 2013. From these occurrences, 40 % had physical impacts, such as damages in basements, commercial stores and private houses, and 42 % registered societal impacts related to traffic disruption due to flooding forcing the public authorities' involvement (Table 6).

The occurrences with the most relevant impacts occurred on 27 February and 2 March 2 2010, during which the Seixal old city centre was partially inundated (Fig. 7). The first occurrence is associated with the Xynthia storm already described in Sect. 2 and was driven by the combination of high tidal level (4.2 m above CD), storm surge (about 0.6 m) and strong wind (maximum intensity of about 100 km/h) directed towards the cost. On 2 March, the flood episode is also related to high tidal level, in this case higher than before (4.3 m above CD), and surge conditions relevant but smaller than in the previous episode (about 0.4 m). Regarding physical impacts, extensive damages in basements and road infrastructures were registered, adding to societal impacts resulting mainly from traffic and services disruption. The acquired in situ data, as a complement of the historical records, show that in the Seixal Municipality, two types of flooding events, based on their frequency and degree of impact, have to be considered in risk management: the high-impact low-frequency events, such as the one on 27 February, and more frequent flooding episodes with less severe consequences occurring during extreme high water levels, particularly forced by tide (equinoctial maximum levels) and atmospheric pressure. The latter result from the water inflow into the urban drainage system and its return by sinks that is

Table 6 Number of occurrences by type of impact in the Seixal waterfront area registered in the L_DB between 2002 and 2013

Type of impact	Total number of occurrences
Occurrences with institutional involvement	48
Human losses	0
Flood damages	19
Traffic disruption	20

Fig. 7 February–March 2010 flooding events: **a** reconstruction of the flooding extension in the Seixal old city centre (image: ESRI Aerial Imagery); **b** aspect of the urban flooding area, 02 March 2010 (image source: Câmara Municipal do Seixal)

intensified during heavy rainfall episodes. The flooding promoted by direct overtopping of the margins is less frequent, but may occur due to the effect of wind waves during extreme high water levels. Depending on the flooding severity, no physical impacts are associated with the low-impact high-frequency events, but traffic and services disruption requires institutional involvement.

4.2 Hazard assessment

The Seixal Municipality waterfront is potentially affected by flooding in all the water-level scenarios with, as expected, higher expression when the sea level rise is considered (Fig. 8). Along the water adjacent fringe, persistent affected areas include the Seixal old city centre and Arrentela and Amora urban areas, road and fluvial interfaces, industrial zones (aquiculture farms, naval shipyards) and military facilities. Due to its low topography (average elevation of 1.93 m above MSL), the Alfeite sand spit shows the most extensive are affected.

The total potential flooded extent varies from 93 to 100 ha for the 20- and 100-year probability scenarios, respectively, increasing to 196 ha for the worst-case scenario (with sea level rise). Similar expression of the significant and extreme degrees of hazard (classes 3 and 4) is obtained for the 20- and 100-year scenarios (30 and 35 % of the total flooded area), extending to 77 % when sea level rise is considered.

4.3 Exposed elements and vulnerability assessment

Following the findings of the territorial vulnerability assessment at the estuary level, the identification of exposed elements and assessment of vulnerability in the Seixal Municipality valued the local dynamics related to mobility and commutation, along with the exposed elements usually considered. Therefore, the exposed elements to estuarine flooding in the Seixal waterfront include residential buildings, road network, military, port and environmental infrastructures—such as water and sewage treatment facilities—and built, cultural and natural heritage such as tide mills, sand beaches and marshlands.

Table 7 summarizes the results of the vulnerability assessment, where the area covered by each input data and parameter of vulnerability, using natural neighbourhood

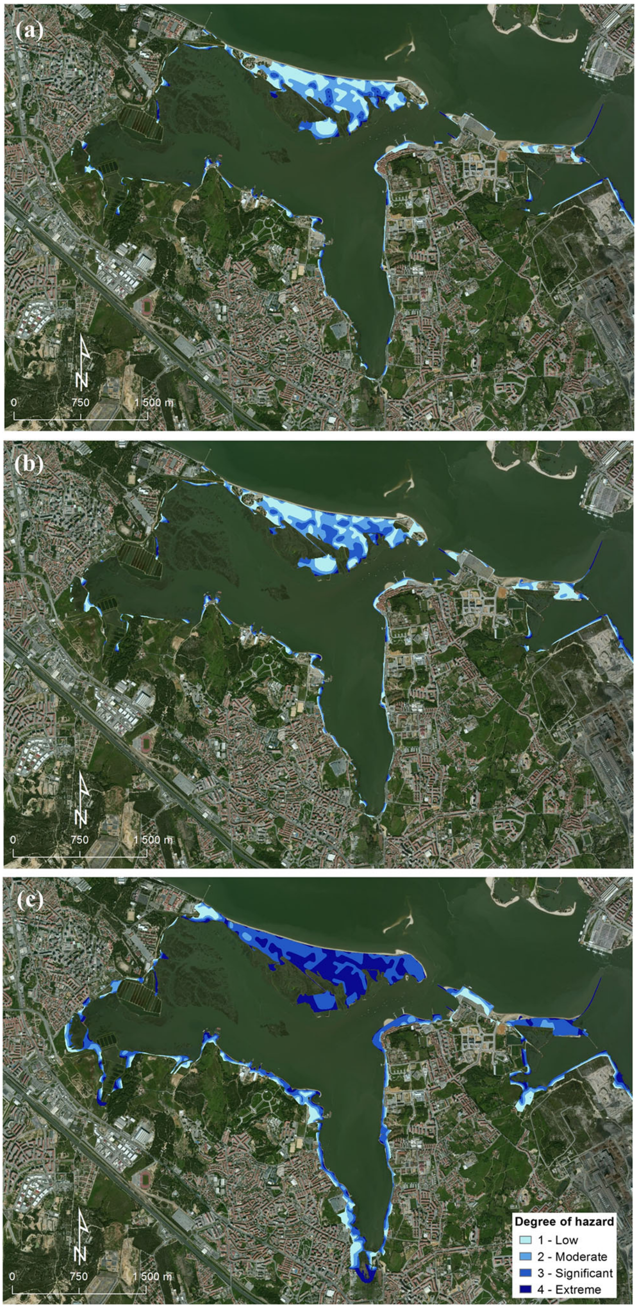

Fig. 8 Flood hazard index classification for different scenarios: **a** 20-year return period; **b** 100-year return period; **c** 100-year return period with sea level rise (image: ESRI Aerial Imagery)

Table 7 Area (hectares) by class of vulnerability in each of the input assessment parameters in the Seixal waterfront area, in the three considered flooding scenarios

	Very low	Low	Moderate	High	Very high	Absence of elements
Road network						
20-year flood	4.717	6.576	2.130	1.705	0.249	77.357
100-year flood	5.088	6.971	2.210	1.742	0.277	83.887
SLR 100-year flood	12.852	14.697	7.937	3.161	0.965	156.814
Built areas						
20-year flood	5.855	1.972	1.445	0.978	0.593	81.774
100-year flood	6.899	2.527	1.870	1.110	0.797	86.973
SLR 100-year flood	14.071	7.332	5.006	3.551	2.804	163.662
Mobility parameter						
20-year flood	8.400	2.502	1.149	0.344	0.000	80.222
100-year flood	10.680	2.680	1.230	0.433	0.000	85.152
SLR 100-year flood	24.425	7.926	4.648	2.348	0.765	156.313
Concentration areas' parameter						
20-year flood	0.000	0.819	0.000	0.092	0.000	91.707
100-year flood	0.000	0.847	0.000	0.092	0.000	99.236
SLR 100-year flood	0.000	6.684	0.000	0.705	0.000	189.036
Environmental infrastructures						
20-year flood	0.000	0.000	0.000	0.000	0.000	92.618
100-year flood	0.000	0.000	0.000	0.028	0.000	100.147
SLR 100-year flood	0.716	0.478	0.304	0.028	1.193	193.707
Area vulnerability (A_v)						
20-year flood	14.643	7.902	2.645	1.339	0.399	65.690
100-year flood	16.691	8.997	2.853	1.400	0.492	69.742
SLR 100-year flood	34.151	20.441	7.488	5.481	4.659	124.206
People vulnerability (P_v)						
20-year flood	0.000	76.705	4.667	9.704	1.542	0.000
100-year flood	0.000	80.138	5.894	12.578	1.565	0.000
SLR 100-year flood	4.368	129.850	26.996	31.505	3.707	0.000
Vulnerability index (I_v)						
20-year flood	14.425	7.557	3.356	1.199	0.391	65.690
100-year flood	16.392	8.662	3.634	1.331	0.414	69.742
SLR 100-year flood	32.749	20.515	10.219	6.621	2.115	124.206

classification, is presented. Road network, built areas, mobility, concentration areas and environmental infrastructures are processed and summarized in area vulnerability (A_v).

The adopted methodology helps in identifying the effects of flooding on both areas with residing and transient population and activities, thus identifying areas that could be affected by both direct and indirect impacts. For example, areas covered by the mobility parameter—which considers vehicles and bus stop locations—are in general higher than areas occupied by buildings, although mostly classified with very low vulnerability.

In between flooding scenarios, the major differences in flooded areas are observed when sea level rise is considered.

I_v is in general very low in all the scenarios considered: 0.14, 0.16 and 0.33 km^2 in the 20-year, 100-year and SLR 100-year, respectively. Also, significant areas threatened by flooding show the absence of exposed elements.

Nevertheless, the distribution of I_v by classes of flood hazard index (I_h) must be considered, because hazard characteristics are not homogeneous in all the flooded areas, justifying therefore the consideration of flood height and velocity in I_h. This analysis (Table 7) shows that the most vulnerable areas (classes high and very high of I_v) present irregular distributions by I_h class, in each of the three scenarios, with some similarities between the 20-year and 100-year flood scenarios for the present MSL, in opposition to the SLR 100-year flood scenario. This behaviour is explained by the fact that human presence (buildings, road networks and infrastructures) often increases with the distance to the shoreline, resulting in that the majority of such areas are only under flood hazard in this last scenario. In both cases, the two higher classes of vulnerability (high and very high) consist of small areas—0.016 and 0.017 km^2 in the scenarios without SLR and 0.087 km^2 in the scenario with SLR.

In accordance with these figures, relevant areas where flood hazard manifests do not present a vulnerability score, i.e. do not overlay with areas where the typology of exposed elements used in the evaluation of area vulnerability (A_v) is found: 0.657 in 0.926 km^2 (71 %) in the 20-year scenario; 0.697 in 1.002 km^2 (69.6 %) in the 100-year scenario; and 1.242 in 1.964 km^2 (63.2 %) in the SLR 100-year scenario (Table 8).

Results presented in Fig. 9 demonstrate such an approach, namely in the areas that resident and transient population use, but where building densities and road network density are low or even absent (for locations see Fig. 5): for leisure, the Alfeite sand spit; for daily commutation, the parking lot of the fluvial station (Transtejo pier); for working, the facilities of the Portuguese Hydrographic Institute (close to Transtejo pier). In fact, flood hazard is affecting essentially functions and not so much residential areas, as the consideration of parameters related to mobility and concentration areas proved adequate in identifying vulnerability.

Nevertheless, the areas with higher vulnerability combine both fixed and transient occupancy of the territory, as is exemplified by the I_v classification in the Seixal old city centre (Fig. 9), which is classified as vulnerable by both components of I_v—people (P_v) and area vulnerability (A_v).

4.4 Risk index

As a product of the vulnerability (I_v) and hazard (I_h) indexes, the risk index (I_r) is maximum where very high values of I_v and I_h coincide. In the 20-year flood scenario (Fig. 10a), the areas classified with very high risk are located in two particular spots: a commercial and residential building block in the Seixal old city centre (OCC), with a vital road section that connects the eastern and western sectors of the study area, a part of the building and dock that compose the fluvial station. In the 100-year flood scenario (Fig. 10b), the same classification of I_r is quite similar to the 20-year scenario, only identifying an additional area inside the OCC with the same vulnerability characteristics. A different expression of the very high risk class is observed in the 100-year flood scenario with SLR (Fig. 10c), with a much larger area represented in the OCC—areas that were classified as of high and moderate I_r, or not affected at all in the scenarios without SLR—along with the identification of a small part of the Amora dwelling located near the waterfront, crossed by a vital

Table 8 Vulnerability index (I_v) classification in the considered scenarios, by area (hectares) and relative frequency by hazard index (I_h)

		I_v class					$I_v = 0$	Total (ha)
		Very low	Low	Moderate	High	Very high		
20-year flood	Total (ha)	14.354	7.586	3.397	1.199	0.391	65.690	92.618
	% of I_v by I_h class							
	1	39.4	27.4	14.9	38.6	76.4	28.3	
	2	36.9	35.6	42.1	21.2	6.8	44.3	
	3	19.4	33.5	35.2	31.4	16.8	21.4	
	4	4.3	3.5	7.8	8.9	0.0	6.0	
100-year flood	Total (ha)	16.321	8.691	3.676	1.331	0.414	69.742	100.175
	% of I_v by I_h class							
	1	36.6	25.1	16.5	42.5	77.7	23.3	
	2	36.6	36.9	30.9	14.9	0.0	41.0	
	3	22.8	34.3	43.1	34.6	22.3	29.2	
	4	4.0	3.7	9.5	8.0	0.0	6.5	
SLR 100-year flood	Total (ha)	32.679	20.544	10.261	6.530	2.206	124.206	196.425
	% of I_v by I_h class							
	1	8.0	13.2	25.0	23.1	5.0	13.2	
	2	9.6	13.7	17.0	26.8	8.8	8.6	
	3	50.5	46.1	34.4	37.7	82.0	39.8	
	4	31.9	27.0	23.6	12.4	4.2	38.4	

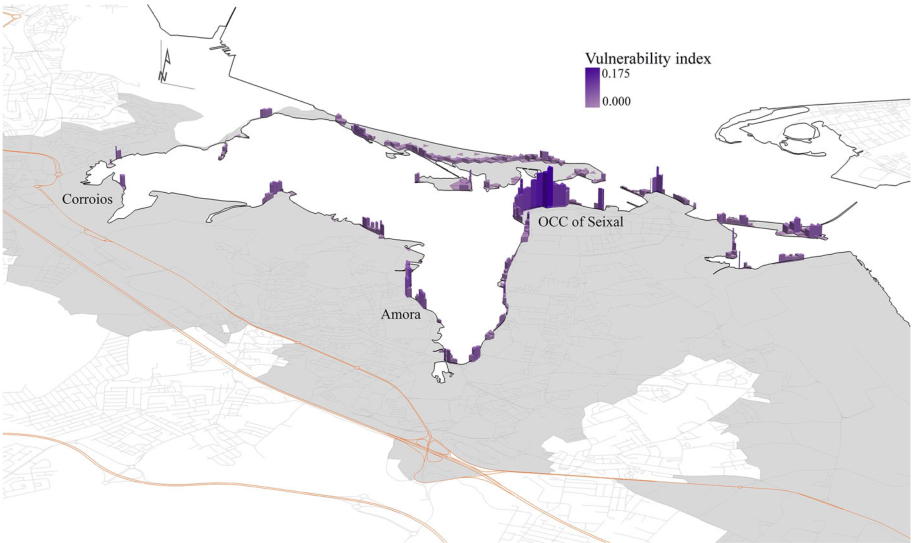

Fig. 9 Vulnerability index in the Seixal Municipality (in *grey*) for the 100-year return period scenario

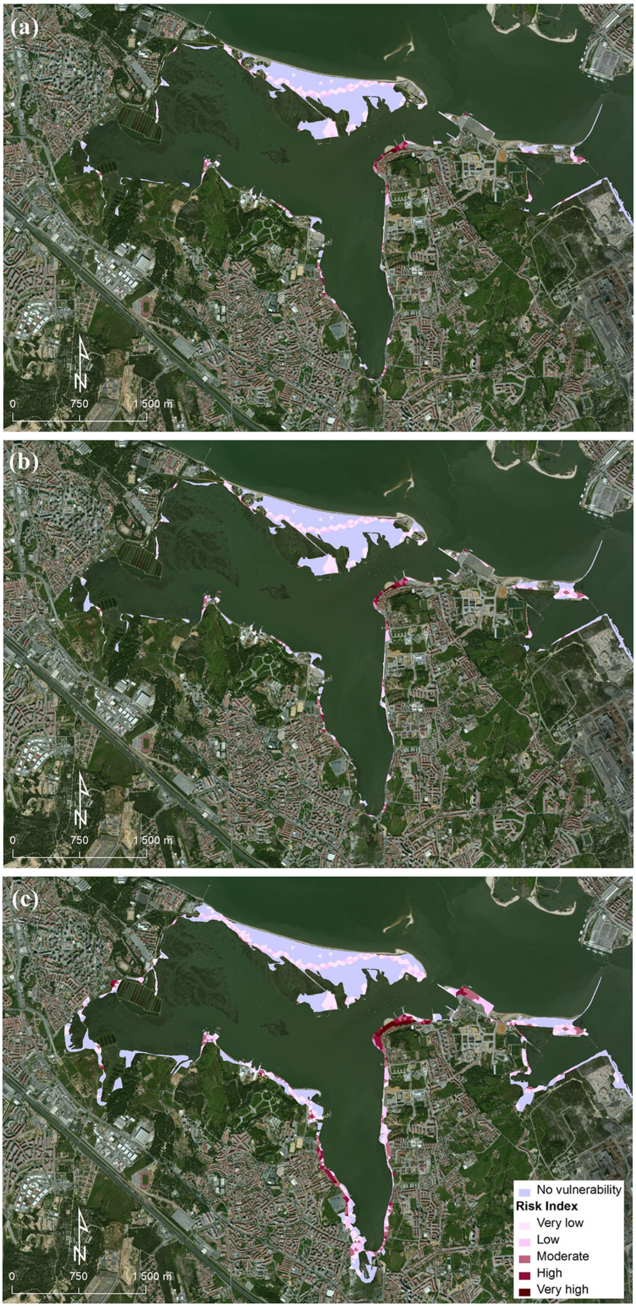

Fig. 10 Flood risk index classification for different scenarios: **a** 20-year return period; **b** 100-year return period; **c** 100-year return period with sea level rise (image: ESRI Aerial Imagery)

road infrastructure and parking lot. The area inside the OCC with higher risk partly coincides with the limits of the statistical block with the higher classification in the people vulnerability (P_v) parameter. In all the flooding scenarios, large areas where flood hazard exists are not overlaid by areas with exposed elements (expressed as no vulnerability in Fig. 10).

In general, the existence of buildings, road network and vehicles are common factors in areas with high and very high risk. Particular spots are equally classified, corresponding to the fluvial station and respective parking lot, and shipyards and buildings related to the naval industry, and a wastewater treatment facility, the last one only affected in the scenario considering SLR (upper left area in Fig. 10c). The risk profile of areas with higher classes of I_r highlights the relevance of mobility and transport planning, the protection and contingency of economic activities and the concern with the more vulnerable population.

5 Decision-making support

The flood risk assessment results at a local scale allowed the definition of a consistent strategy to support different levels of the decision-making process. To support emergency planning, an early warning system was implemented for the locations with the highest risk of flooding. Preventive actions for flood severity reduction and impact mitigation, based on land-use and occupation planning measures, are proposed.

5.1 Critical points characterization

Along the Seixal waterfront, eleven critical points are representative of the locations with the highest risk of flooding (e.g. the Seixal old city centre) or crucial locations for the road and fluvial connectivity functions (e.g. the Transtejo fluvial station, Amora) (Fig. 11). This information is relevant for the emergency planning, enabling to anticipate the required civil protection resources.

Each critical point represented in the early warning system refers to areas identified as critical in the exposed elements and vulnerability assessment. Table 9 resumes, for each point, the type of affected elements and socio-economic functions, in the flooding scenarios of 20- and 100-year return period at present MSL. The typology of the exposed elements in the critical points located closer to the flood-prone areas is similar for both scenarios, showing differences in the quantity of elements exposed as the number of buildings affected. A particularly vulnerable point is the road access in the Alfeite sand spit (#1) as there is no alternative access to buildings, public and military infrastructures and piers.

Some critical points refer to areas with little or negligible residential and commercial occupation. In such areas, specific exposed elements and functions are affected: related to fluvial and maritime socio-economy (#5, #7 and #10); related to aquaculture and fisheries (#2, #3 and #4); related to the access to sand spits or road dead ends (#1, #2 and #11), with a particular significance to the access to military facilities.

In contrast, the remaining three critical points (#5, #7 and #10) refer to consolidated urban areas usually characterized by the presence of parking lots, vehicles and public gardens, along with residential and commercial buildings. Disruptions in the road networks are a type of affected function which is common to almost all the critical points.

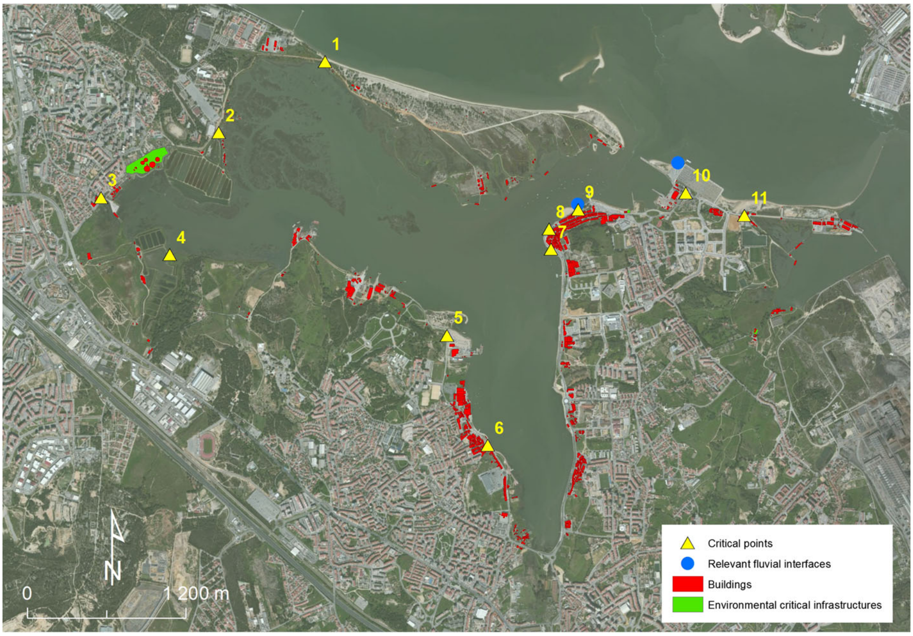

Fig. 11 Critical points for the flood early warning system and potential affected elements (image: ESRI Aerial Imagery)

5.2 Early warning and emergency planning guidelines

The previous results brought significant advances in the knowledge regarding flooding in the Tagus estuary under the influence of tide, wind and storm surge conditions—its hazard process and respective exposed elements and vulnerability. Based on this, spatial planning and emergency guidelines for disaster risk reduction can be defined.

In terms of emergency planning, the acquired knowledge regarding the spatial expression and time recurrence and forecast of flooding events has allowed municipal civil protection authorities to define detailed procedures in terms of optimizing each civil protection agents' role in risk communication and emergency response.

5.2.1 Early warning system

An early warning system was built taking advantage of the detailed forecasts developed for the Seixal area. The objective was to disseminate timely useful information about the likely time and severity of the flood to the civil protection agents, for them to take effective action in response.

Products available at the WebGIS interface were created using information at the several critical points defined above, following the integration approaches: (1) overview of all early warnings, organized by parish geographical location and alert level (defined in 3.3) with direct access to detailed information of the critical points in each parish that fit in the selected alert range; (2) map view of the alert level at each critical point, along with the detailed prediction of this alert level in the 48-h forecast window (Fig. 12); (3) time series

Table 9 Type of affected features and functions in the critical points

Critical point	Dominant risk index class[a]		Type of affected features and functions[b]																
	20-year	100-year	RN	RB	CB	AB	CH	W	PG	V	P	D	Sy	S	FS	FH	Aq	Am	M
1—Restinga do Alfeite	VL/L	VL/L	x		x							x		x					x
2—Varejeira	VL/L	VL/L												x		x			
3—Ecomuseu Moinho	VL	VL															x	x	
4—Corroios	VL/L	VL/L	x	x				x									x		
5—Atalaia	L/M	L/M	x									x	x	x					
6—Praça 5 de Outubro	L/M	L/M	x	x	x			x	x	x		x		x					
7—Curva da Mundet	M/H	M/H	x							x	x	x		x					
8—Igreja do Seixal	H/VH	H/VH	x	x	x		x		x	x	x								
9—PCP do Seixal	M/H	M/H	x	x	x				x	x	x	x		x					
10—Terminal da Transtejo	H/VH	H/VH										x	x	x	x				
11—IH Azinheira	VL/L	L/M	x			x		x		x	x								x

[a] *VL* very low; *L* low; *M* moderate; *H* high; *VH* very high

[b] *RN* road network; *RB* residential buildings; *CB* commercial buildings; *AB* administrative buildings; *CH* cultural heritage; *W* warehouses; *PG* public garden; *V* vehicles; *P* parking; *D* docks; *Sy* shipyard; *S* ships; *FS* fluvial station; *FH* fishery houses; *Aq* aquaculture; *Am* access to museum; *M* access to military facilities

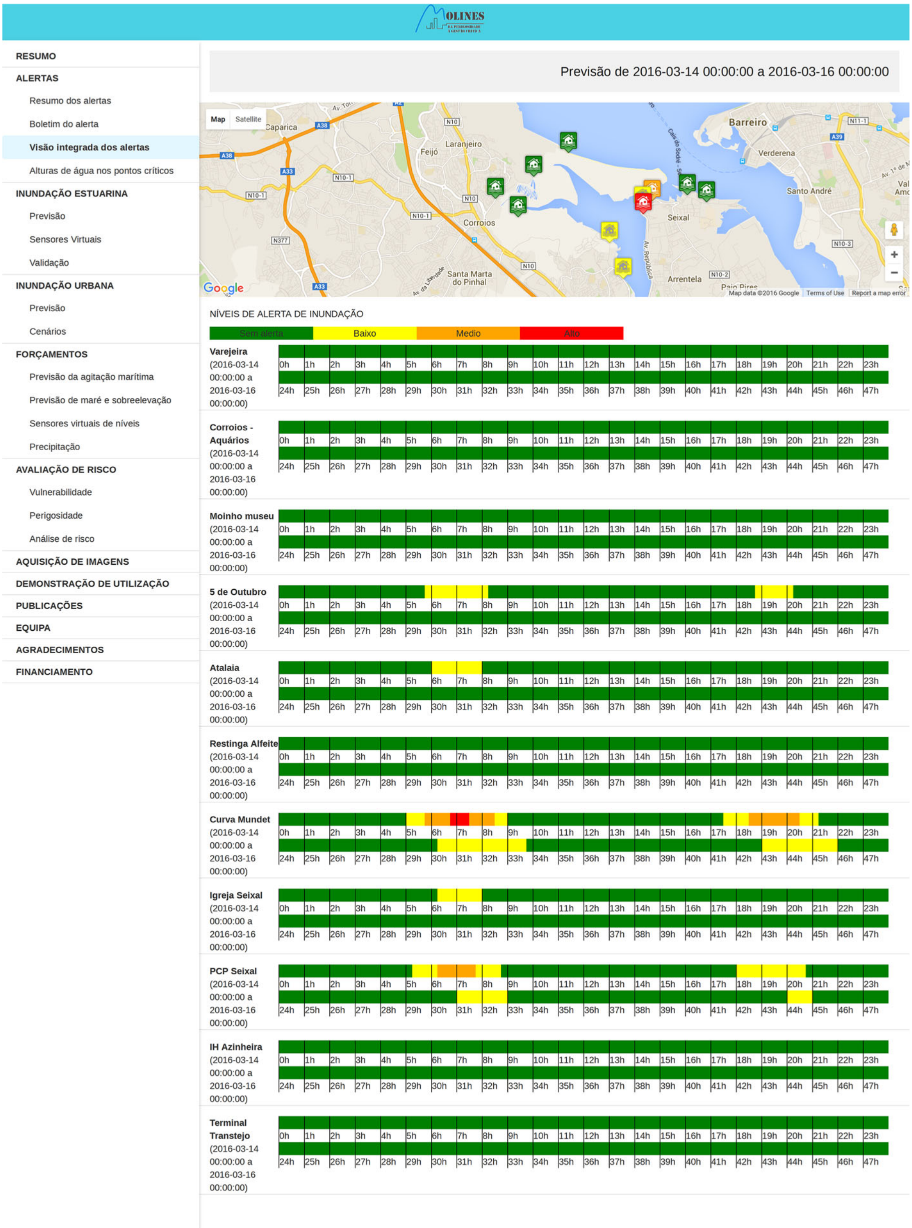

Fig. 12 Early warning detailed view for the Seixal Municipality: alerts for the critical points

of water heights at the critical points when the alert level exceeds the "no alert" threshold (Fig. 13). When the threshold of "no alert" is exceeded, the interface provides Web access to the early warning bulletin, which is also automatically sent by email to the relevant civil protection agents. The bulletin includes the relevant spatial and temporal information associated with the warning: map of the critical points; alert level at each critical point in

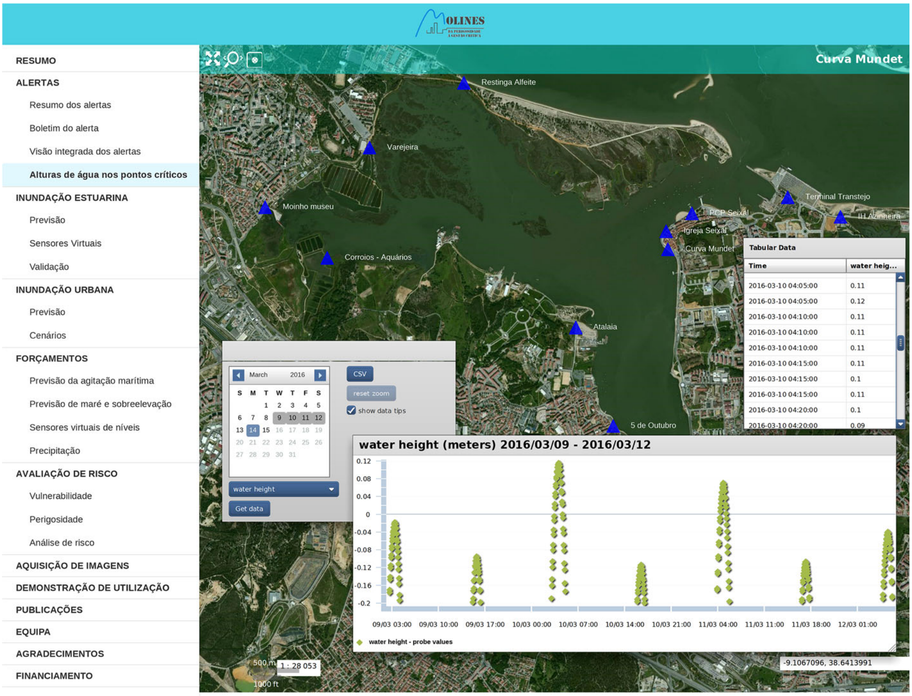

Fig. 13 Time series of water heights at the critical points

the 48-h forecast window; a summary of the maximum water height, wind intensity and atmospheric pressure during the same forecast window; information about each warning level (definition and possible impacts). The information provided by the interface assists civil protection agents to timely identify resources for the emergency response and to help take decisions to prevent flood damages and other indirect impacts.

5.2.2 Emergency planning guidelines

The definition of guidelines for the emergency planning is based on the data and tools previously obtained—in summary, the results of the risk assessment and the early warning system. The guidelines are sequenced accordingly to four emergency management stages (Fig. 14). As illustrated, the starting point for the entire process is the set-up of a list of monitoring routines with the objective of informing about present and predicted water levels and, when necessary, the subsequent dissemination for support of the following stages.

The sequence of stages is framed and structured by the Seixal Municipality emergency plan. Depending on the level of the alert, this planning instrument might be activated or not. In the same context, an evaluation of the capacity of municipal resources to deal with the imminence or factuality of an emergency is performed, following the standard procedures to be included in the emergency plan, and accordingly, supramunicipal resources are or not requested.

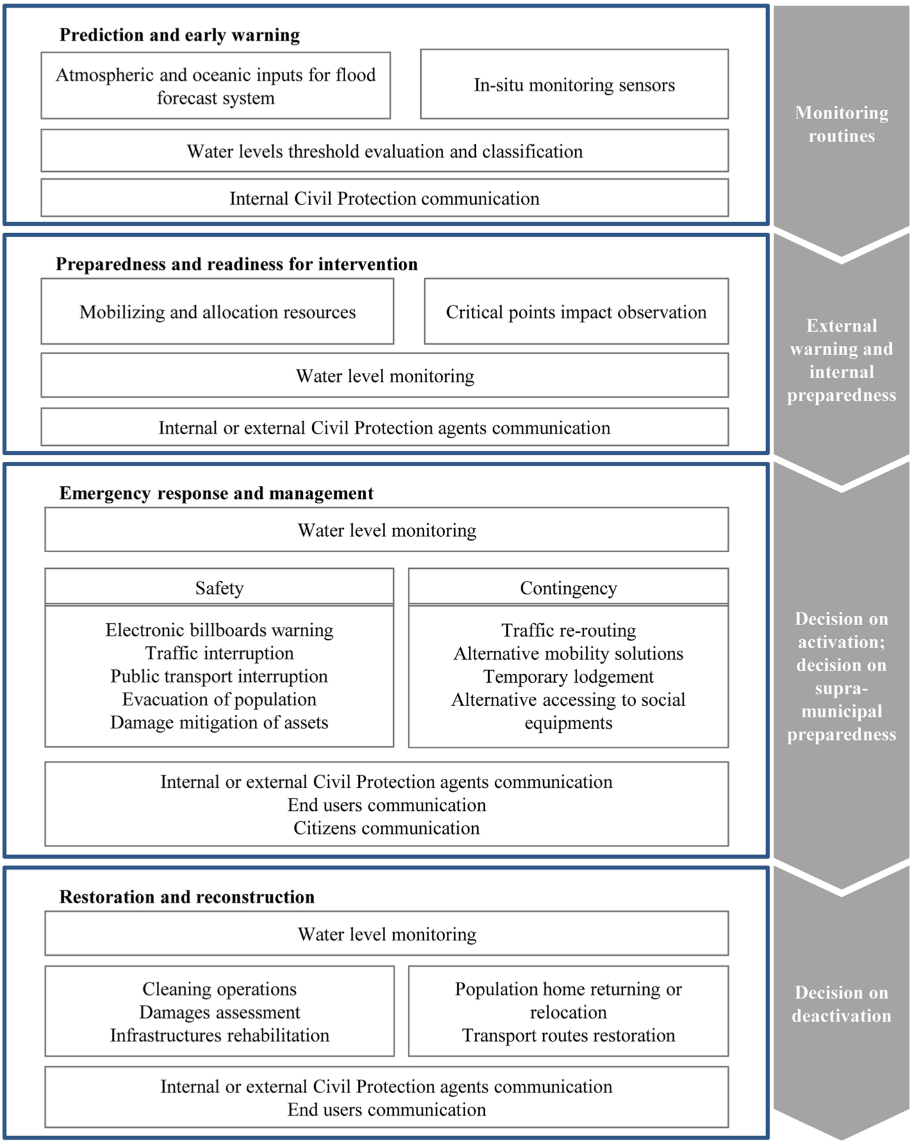

Fig. 14 Guidelines for the emergency management stages (in *grey boxes*: framing in the emergency plan)

Emergency response and management is devoted to ensuring the safety and contingency of people, functions and assets, with a focus on mobility. Transversally to all phases, the water levels are continuously monitored in order to support the decision of civil protection agents.

Finally, internal communication between civil protection agents is present in all stages. The involvement of other sectoral end-users (from the health, education, transport, economic or social fields) as well as communication to the citizens is foreseen and regulated in the emergency plan. This wider communication scope is limited to the last three stages described in Fig. 14—preparedness and readiness for intervention, emergency response and management and restoration and reconstruction—because in the prediction and early warning phase the information is conveyed uniquely between the municipal civil protection agents.

5.3 Spatial planning guidelines

Risk reduction from coastal flooding is becoming an increasingly difficult task. Urban waterfronts are coveted by real estate agents, as the value of prime locations and views over the estuary come at a premium. Former industrial and port areas present unique opportunities for centrally located urban development (ULI 2004; Brown 2008). At the same time, sea level is rising and posing an ever-increasing threat to urbanized shorelines and natural systems (Hallegatte et al. 2013; Fitzgerald et al. 2008; Nicholls and Cazenave 2010). Wetlands are now increasingly "squeezed" (Torio and Chmura 2013; Kirwan and Megonigal 2013) between rising sea waters and encroachment by flood defence infrastructures. While passive flood risk management has been appropriate in some contexts, future challenges will demand a more proactive adaptation stance.

In selecting the recommended planning guidelines for the Seixal waterfront, a set of 26 possible adaptation actions were identified, from the relevant literature (FLOODsite 2009; EEA 2013; Gersonius et al 2008; Wilby and Keenan 2012; Hallegatte 2009; Hamin and Gurran 2009; Poussin et al. 2012; Arkema et al 2013; CCAP 2011) and observation of local conditions along the Tagus Estuary. The 26 actions were then qualified according to their cost (low to high), the scale of intervention/scope (small/dwelling, to large/regional or national scale), the time horizon for full implementation (from short/less than 2 years to long/over 25 years) and regrets (no regrets being solutions that will provide benefits regardless of whether flood risk increases, whereas high regrets solutions are those that, if implemented, would adversely impact other measures of environmental performance or be too costly to revert).

The rating of each action is derived from the acquired experience with the Seixal/Tagus estuary-specific situation and is naturally subjective and context dependent. For instance, some "soft" adaptation actions are relatively easy to approve in Portuguese legislation, since there is enough public/political support for them. In other contexts, such as the USA, changing or updating legal documents may be a much more strenuous effort, especially when land rights are involved (Eichenberg 2013; Davoren 1982). At the same time, some more costly structural measures would likely face serious financing constraints.

Based on these ratings and how adequate/easy to implement they would be for the specific context of Seixal, a subset of actions were selected to recommend as steps in increasing the resilience in face of coastal flooding and future sea level rise (Table 10).

Some of the actions indicated have already been completed (the Municipal Land-Use Plan of 2014, for instance, addresses the delimitation of vulnerable areas, limited the construction of basements and expanded the protection of wetlands), while other actions (such as the remodelling of waterfront public spaces so as to provide flood protection) would require future action. While quite a few of the actions (1–11) address problems already experienced during exceptional storm surges, others (12–19) should be part of a long-term strategy to minimize the impacts of expected sea level rise. All but four of the actions are considered as no- or low-regret, that is they provide multiple benefits and/or are beneficial even if the more adverse impacts of climate change do not materialize.

Table 10 Selection of adaptation actions to coastal flooding and sea level rise in the municipality of Seixal

	Action	Time horizon	Cost	Scale	Regrets	Implemented in Seixal?	Agents
1	Equip vulnerable dwellings with removable, fixed or automatic flood gates for doors, windows, air holes and garage doors	1–2 years	Low	Dwelling	Low	No	Home and store owners (installation), municipality and parishes (supervision)
2	Implement formal system of road signs providing warning of flooded roadways and sidewalks	1–2 years	Low	Dwelling	Low	No	Municipality (installation), civil protection agents (supervision)
3	Protect existing wetlands, beaches and dune systems	1–2 years	Low	City/region	No	Yes	Municipality (planning instruments), environment agency (management)
4	Identify safe routes alternative to flood-vulnerable roadways and transit lines	1–2 years	Low/medium	Block	No	Partially	Municipality, civil protection agents, public transportation companies
5	Forbid the construction of basements in flood-prone areas	3–10 years	Low	Dwelling	Low	Yes	Municipality
6	Forbid new construction in vulnerable areas through local planning instruments	3–10 years	Low	Neighbourhood	Low	Partially	Municipality
7	Remove valuable or perishable items and sensitive infrastructure from basements and flood-prone ground floors	3–10 years	Low/medium	Dwelling	Low	Partially	Home and store owners (implementation), municipality (supervision)
8	Install water pumps on all basements, underground garages, or ground floors below flood stage	3–10 years	Low/medium	Dwelling	Low	No	Municipality, home and store owners
9	Implement early flood warning and monitoring systems (SMS, media alerts, sirens, etc.)	3–10 years	Medium/high	City/region	Low	Partially	Civil protection agents
10	Actively manage existing wetlands so as to increase their resilience and promote their expansion	3–10 years	Low/medium	Neighbourhood	No	No	Environment agency (planning/managing), municipality (assistance)
11	Map risks, highlight vulnerable areas, and increase awareness	3–10 years	Low/medium	Block	No	Yes	Municipality

Table 10 continued

	Action	Time horizon	Cost	Scale	Regrets	Implemented in Seixal?	Agents
12	Transfer machinery, generators, elevator shafts to higher floors	3–10 years	Medium/high	Dwelling	Medium	No	Home and store owners (installation), municipality (supervision)
13	Improve storm water drainage systems by replacing pipes, introducing tidal valves, pumping stations or reservoirs	10–25 years	Medium/high	Neighbourhood	Low	Partially	Municipality
14	Raise waterfront parapets/guards to increase protection against low flood levels or wave spillover	10–25 years	Low/medium	Neighbourhood	Medium	No	Municipality
15	Raise waterfront public spaces and/or design them so as to double as barriers against flooding	10–25 years	Medium/high	Block	Medium	No	Municipality
16	Reduce peak surface runoff by introducing green infrastructure and improving infiltration and detention	10–25 years	Medium/high	Neighbourhood	Low	No	Municipality (planning, major features), home owners, parishes (small features)
17	Enact changes to flood risk insurance policies so as to increase accountability for “risky” location choices	10–25 years	High	City/region	High	No	Central government
18	Revise building standards so as to require higher ground floor clearance on new buildings or reconstructions	+25 years	Low	Neighbourhood	Low	No	Municipality
19	Create new artificial wetlands, namely by reconverting underused reclaimed landfill areas	+25 years	High	City/region	Low	No	Baía do Tejo society, environment agency, South Bay project, municipality

6 Concluding remarks

The management of flood risk in estuaries requires an integrated view considering the multiplicity of hazard-forcing factors acting in these systems, as well as their territorial and social complexity. An innovative approach to support flood risk management in estuaries is presented at a local scale. The approach is built upon a previous regional framework of the study area and integrates different methodological tools. Historical information contributes to support and validate the hazard assessment for different flooding scenarios based on numerical modelling. The exposed elements and territorial vulnerability assessments are integrated with the hazard results to support the comprehensive risk analysis at a local scale. Two levels of the decision-making process are addressed in this study: the early warning and emergency planning, and the reduction and impact mitigation. An early warning system implemented for the locations with the highest risk of flooding and a set of emergency planning guidelines will assist the municipal civil protection authorities in preparedness and emergency response. Increasing flood resilience actions, based on land-use and occupation measures, are proposed as possible contribution to territorial planning instruments.

The information and tools that result from this work enable decision-makers to address flood risk in estuaries at a local scale, contributing to their institutional capacity-building, and contributes to promote more resilient communities, fulfilling one of the Sendai Framework for Disaster Risk Reduction priorities.

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