An Integrated Approach for Flood Risk Assessment in Estuaries

P. Freire, [1], A. Tavares [2], A. Fortunato [1], A. Oliveira [1], M. Cardoso [1] and P. Pires [3]

(1) Laboratório Nacional de Engenharia Civil. Av. do Brasil, 101 1700-066 Lisboa. pfreire@lnec.pt

(2) Centro de Estudos Sociais, Universidade de Coimbra. Largo D. Dinis, Apartado 3087 3001-401 Coimbra

(3) Autoridade Nacional de Proteção Civil. Av. do Forte em Carnaxide 2794 - 112 Carnaxide

Abstract: Floods in estuaries are associated to different hazard sources, such as high tide levels, storm surges and large fresh water discharges. In adjacent urban areas, the impact of estuarine high water levels is often amplified due to inadequate drainage conditions. As requested by the European Directive on Floods, flood risk assessment and management is becoming a priority as the effects of climate change and the growth of exposed population will increase inundation vulnerability. An integrated approach for flood risk assessment was developed, in which inundation for different climate scenarios and return periods is evaluated through estuarine and urban drainage numerical modelling. Exposed elements assessment, including population, infrastructures and environmental resources, supports territorial vulnerability mapping, and risk is analysed considering different spatial scales (regional and local) and territorial topologies (urban and interface). Results will contribute to improve the understanding of estuarine inundation processes and to develop adequate flood risk management guidelines.

Key words: numerical modelling, climate change, territorial vulnerability, management guidelines, alert and warning system

1. INTRODUCTION

Estuarine margins are particularly vulnerable to floods from different sources. High water levels in estuaries result from extreme conditions such as the coincidence of high tidal levels with storm surge episodes or with large fresh-water discharges (Townend and Pethick, 2002). In adjacent urban areas estuarine water levels can constrain surface and sewer drainage systems capacity, particularly during episodes of intense and concentrated in time rainfall. Rising sea levels and more extreme climate conditions (IPCC, 2013; Vermer and Rahmstorf, 2009; Rahmstorf, 2010) will increase the inundation hazard in estuarine margins. In the presence of this complex phenomenon flood risk assessment in estuaries is not compatible with the methodologies applied to coastal and fluvial areas and specific approaches for estuarine environments should be developed.

The project MOLINES - *Modelling floods in estuaries. From the hazard to the critical management*, presented in this paper, aims to improve the understanding of inundation processes in estuaries, to assess flood risk of estuarine margins with different typologies and from different sources, and to develop flood risk management guidelines that are adequate for transition areas. In this project, flooding in adjacent areas of estuaries is addressed considering the different hazards in an integrated way, with reference to the contribution of the EU/ EXIMAP (2007), as well as the objectives of the European Directive on Floods. Due to its socioeconomic relevance and particular hydro-morphological characteristics, the Tagus estuary was chosen as study area.

2. CASE STUDY

The Tagus estuary, located in the Portuguese west coast (Fig. 1), is one of the largest estuaries in Europe with an area of about 320 km^2. The estuary is included in the territorial unit of Lisbon and Tagus Valley, involving 18 municipalities in the metropolitan area of Lisbon, with about one million inhabitants directly or indirectly exposed (INE, 2012). Its margins are intensively occupied and include the most important infrastructures, equipment and strategic services on national level. Occupation contrasts are evident on its margins: in the western and northern sides urban (34% of the total margin area) and industrial/port facilities (24%) are the dominant types of occupation, while agriculture (35%) and isolated towns occupy the most area of its eastern and southern margins (Rilo *et al.*, 2012).

The estuary presents a complex morphology, with a deep and narrow inlet channel and a broad and shallow inner basin, where the intertidal area is about 43% of the total estuarine surface (Nogueira Mendes *et al*., 2012). These particular characteristics control tide propagation within the estuary, promoting tidal amplitude increase towards upstream due to resonance effects (Fortunato *et al*., 1999). By its narrow entrance, the inner estuary is protected from ocean wave incursion, but its elongate shape in the prevailing wind direction, from the northeast, promotes local generation of waves (Freire and Andrade, 1999; Freire *et al*., 2009). The main source of fresh water into the estuary is the

Tagus River with an average discharge of about 370 $m^3 s^{-1}$ (Neves, 2010).

The particular morphological settings of the Tagus estuary and its hydrodynamic conditions promote high risk to estuarine margins flooding (Vargas *et al.*, 2010; Rilo *et al.*, 2013), well-illustrated in past events, as the February 15th 1941 windstorm that caused high human casualties and property damages along the estuarine margins (Muir-Wood, 2011).

Fig. 1. Location of the Tagus estuary (image from: Bing Maps Aerial Imagery Web Mapping Service).

3. METHODOLOGICAL APPROACH

The methodological approach of MOLINES project is grounded in four interlinked work blocks (Fig. 2), and develops into two different spatial scales, at the estuary and local levels. The approach will assume a scenario of anthropogenic development contention for land occupation dynamics, and considers the climate scenarios defined by international and national studies (IPCC, 2013; Santos and Miranda, 2006).

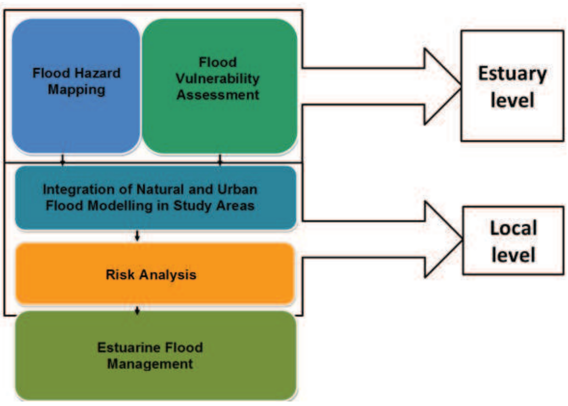

Fig. 2. Methodological approach followed in MOLINES project.

3.1. Flood hazard mapping

To improve the understanding of how past flood events affected estuarine margins and which are the flood forcing dominant factors, a geographic database of historical flood events that affected estuarine margins is constructed through the analysis of the accessible information, including newspaper, technical and scientific publications, and municipal and civil protection records. The possible flood drivers (tide, storm surge, wind, waves, precipitation and fresh-water discharges) of selected higher impact events were evaluated and the results used to validate the models results.

The flood-prone area extension of the estuary is predicted through a hydrodynamic numerical model, forced by tide and storm surge, considering different return periods and sea level rise scenarios. Flood hazard map are constructed, following the good practices recommendation from EU/EXIMAP (2007), based on the predicted inundation levels and a detailed digital elevation model (DEM) updated with the topographic and bathymetric available information. The inundation extension is analysed and compared with the historical flood events information.

3.2. Flood vulnerability assessment

To support the vulnerability analysis, the evaluation of estuarine exposed elements includes: the exposed population (resident and floating) and commuting flows; the identification and characterization of built infrastructure and equipment installed; vital services and functions to society as the critical elements associated with the civil protection and emergency management; present environmental elements. To compare the territorial exposure to estuarine floods, a composite community vulnerability index based on a set of indicators and supported by a descriptive statistics, is built. The contrasts between inundation-prone areas are expressed by the cartographic classification of the estuarine vulnerability index (Chen *et al.*, 2013).

3.3. Integration of natural and urban flood modelling in study areas

Due to the territorial diversity of the Tagus estuary, a refinement of territorial typologies is important to completely characterize the flood hazard and risk consequences. Therefore, two territorial typologies were identified as representative of that diversity: urban and interface areas (Freiria and Tavares, 2011). The latter are defined as natural regions on which human presence is persistent due to the natural resources of those areas, e.g. salt pans, old tide mills or aquaculture structures and even agriculture parcels (Bossard *et al.*, 2000).

The historical data information, the hazard and vulnerability mapping results allow the identification of the most urban and interface vulnerable areas to flood. These areas are studied within a detailed scale, using an innovative approach that combines estuarine hydrodynamic and urban drainage modelling. A set of simulations are carried out taking into account different rainfall event intensities and different estuary water levels, in order to forecast inundation levels, velocity and extension of flooding events.

3.4. Risk analysis

Flood hazard assessment for the detailed study areas are based on the numerical modelling results. The hazard assessment takes into account different parameters such as spatial-temporal development, severity and likelihood of occurrence. As this analysis is integrated in a Geographic Information System (GIS) and stored in a layers database, it is possible to obtain a cartographic representation of the consequences and therefore getting a framework hazard vision, as result of an integration of the standardized classes.

Risk assessment involves the evaluation of the human exposure, the sturdiness and characteristics of structures affected, and the characterization of the intrinsic characteristics of the social vulnerability and the affected societal (social, economic, cultural, civil protection) functions. The results provide an innovative integrated index for damage evaluation for each study area, considering the different territorial typologies (urban and interface). This damage index, providing information on the consequences of flood events, is integrated with the probability of events occurrence (return periods) to assess flood risk of the study areas (Santos *et al.*, 2014).

3.5. Estuarine flood management guidelines

With the previous results, a consistent knowledge of the flooding processes and impacts on the study system is obtained, which assures a design of new integrated management measures that can be applied to other areas. The aim of these management vectors, which are supported by new scientific data and models, is assessing two different scales of intervention, municipal and regional, framed by the Municipal Master Plans and the Regional Master Plan, the Estuarine Managing Plan and the associated coastal plans under revision.

These guidelines consider three different management vectors: preventive measures related to land use and occupation planning; proposal of some structural and non-structural actions for flood severity reduction and for impact mitigation on the different spatial patterns; improvements on the alert and warning system, based on the extension of an existing real-time forecast platform to inundation purposes (Rodrigues *et al*., 2013). Improvements on the alert and warning system are based on predictions of threshold water level, provided by the extension of the existing nowcast-forecast system of the hydrodynamics of the Tagus estuary (http://ariel.lnec.pt) to inundation purposes.

4. FINAL REMARKS

A new methodological approach to address flood risk analysis in estuaries, due to several drivers (tide, storm surge, wind, waves, precipitation and fresh-water discharges), is under development in the MOLINES project.

The main innovative aspects of this methodology are the integration of different strategies that are typically used independently in flood risk analysis, as estuarine hydrodynamic modelling and urban drainage modelling, and the use of two different spatial scales of analysis (estuarine and urban).

The research objectives provide a regional level of analysis whose results support and implement the objectives of the European Floods Directive and are in line with the main national strategies as the National Strategy for Sustainable Development, the National Program of Policy Territorial Planning Policies, or the National Program for Climate Change.

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