Universidade de Aveiro Departamento de Física
2012

Juliana Marques Valentim da Silva

Efeito da hidrodinâmica nos sapais da Ria de Aveiro e estuário do Tejo

Hydrodynamic effects in Ria de Aveiro and Tagus estuary salt marshes

Universidade de Aveiro Departamento de Física
2012

Juliana Marques Valentim da Silva

Efeito da hidrodinâmica nos sapais da Ria de Aveiro e estuário do Tejo

Hydrodynamic effects in Ria de Aveiro and Tagus estuary salt marshes

Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Ciências do Mar e das Zonas Costeiras, realizada sob a orientação científica do Doutor João Miguel Sequeira Silva Dias, Professor Auxiliar do Departamento de Física da Universidade de Aveiro e co-orientação da Doutora Maria Helena Abreu Silva, Professora Auxiliar do Departamento de Biologia da Universidade de Aveiro.

Este trabalho foi desenvolvido no âmbito dos projetos ECOSAM (PTDC/AAC-CLI/104085/2008) e DyEPlume (PTDC/MAR/107939/2008) com o apoio financeiro da Fundação para a Ciência e Tecnologia - FCT

o júri

presidente

Prof.ª Doutora Filomena Maria Cardoso Pedrosa Ferreira Martins
Professora Associada do Departamento de Ambiente e Ordenamento da Universidade de Aveiro

Doutor Nuno Alexandre Firmino Vaz
Investigador auxiliar do CESAM e Departamento de Física da Universidade de Aveiro

Prof. Doutor João Miguel Sequeira Silva Dias
Professor auxiliar do Departamento de Física da Universidade de Aveiro

Prof.ª Doutora Maria Helena Abreu Silva
Professora auxiliar do Departamento de Biologia da Universidade de Aveiro

acknowledgements

I would like to thank many people who helped, supported and participated to carry on the present study.

To my supervisor, Prof. Doutor João Miguel Dias, for his scientific supervision. Most important, thank you for all your support, help, patience, trust and friendship in the last three years.

To my supervisor, Profª. Maria Helena Abreu Silva, for her scientific supervision, patience and trust, not only in this study but also in the other issues of the academic field.

To Doutor Nuno Vaz for his patience to help me in the Mohid introduction, to solve several problems at any time and for the constant availability for the clarification of any doubts.

Thanks to Bernardo Duarte and Thiago Couto for helping with the field samples.

Thanks to all my friends and colleagues of NMEC (Estuarine and Coastal Modeling Division) for the exchange of knowledge and ideas throughout my work. A special thanks to Magda Sousa, who supported and helped me since my first day in the “lab” and who always was available to solve any problem, and to Renato Mendes, Leandro Vaz and Ana Azevedo, whose help was especially crucial in last months before the end of this study.

Thanks to my all friends and family who were always present in my studies and in my life at every moment.

palavras-chave

Modelação hidrodinâmica, sapais, *Spartina maritima,* Ria de Aveiro, estuário do Tejo

resumo

Enquanto áreas de transição, os sistemas costeiros apresentam uma enorme variedade e riqueza, proporcionando importantes atividades económicas e sociais. Atualmente, uma das ameaças a estes sistemas é o aumento do nível médio do mar, uma vez que o seu impacto poderá ter efeitos nos seus padrões hidrodinâmicos e, consequentemente, no seu valor ecológico e biológico.
O estuário do Tejo e a Ria de Aveiro constituem dois dos sistemas costeiros mais importantes em Portugal. O estuário do Tejo é um dos maiores estuários da europa e é a zona húmida mais extensa do território português. Por sua vez, a Ria de Aveiro, é a mais extensa laguna do país e a mais dinâmica em termos de processos físicos e biogeoquímicos. Ambos apresentam extensas zonas de sapal, os quais representam um dos mais produtivos ecossistemas da biosfera.
Os sapais são importantes áreas de interface entre a terra e o mar, fornecendo um habitat único para um vasto número de espécies, o que os torna num elemento fundamental na estrutura ecológica dos sistemas costeiros. No entanto, a interação de alguns aspetos físicos e biológicos bem como os efeitos do aumento do nível do mar, são ainda difíceis de explicar.
Um dos objetivos deste estudo foi, recorrendo a um modelo numérico bidimensional, avaliar a influência de certos parâmetros hidrodinâmicos na dinâmica dos sapais do estuário do Tejo e da Ria de Aveiro, nomeadamente nas plantas de sapal, considerando quer o nível médio do mar atual quer um cenário de aumento do nível médio do mar. Os parâmetros hidrodinâmicos estudados foram a circulação residual, a assimetria de maré e a dissipação de energia. Para atingir estes objetivos, além de recorrer a simulações hidrodinâmicas, foi monitorizado um sapal de três em três meses em cada sistema durante um ano e amostras de sedimento e da planta *Spartina maritima* foram recolhidos para assim determinar a área de cobertura e a biomassa aérea e subterrânea da planta e a matéria orgânica e a humidade relativa do sedimento. Os resultados do modelo indicam que os parâmetros hidrodinâmicos em análise poderão explicar as diferentes características bióticas e abióticas que foram encontradas nos dois sapais, em resposta às diferentes condições hidrodinâmicas. Os resultados indicam ainda que o aumento do nível médio do mar poderá afetar significativamente a hidrodinâmica destes sistemas, mostrando como podem evoluir neste cenário. Adicionalmente, as alterações na hidrodinâmica poderão induzir modificações nos parâmetros bióticos e abióticos que, por sua vez, influenciam os sapais. Deste modo, o atual equilíbrio destes ecossistemas poderá ser afetado.

keywords

Hydrodynamic modelling, salt marshes, *Spartina maritima* ,Ria de Aveiro, Tagus estuary

abstract

The importance of the coastal systems such as estuaries and lagoons has been recognized a long time ago. As interface areas, these systems are highly variable and rich, supporting important economic and social activities. The sea level rise impact in coastal systems is an important concern, once it might represent important effects in these systems hydrodynamics and consequently in theirs ecological and biological values.

Two of the more important coastal system of Portugal are the Tagus estuary and the Ria de Aveiro lagoon. Tagus estuary is one of the largest estuaries of Europe and is the most extensive wetland area of Portuguese territory. Likewise, Ria de Aveiro lagoon is the most extensive shallow lagoon system in Portugal and the most dynamic in terms of physical and biogeochemical processes. Both systems have extensive intertidal areas, including salt marshes, which are among the most productive ecosystems of the biosphere.

Salt marshes are a critical interface between land and sea, providing a unique habitat for a large number of species, being an essential element in coastal systems ecological structure. However, the knowledge of some physical and biological interactions within salt marshes, as well as sea level rise effects in these ecosystems, are still difficult to explain.

One of the main goals of this work was to evaluate the influence of the hydrodynamic patterns of Tagus estuary and Ria de Aveiro lagoon in their salt marsh dynamics, namely, in salt marsh plants, considering the actual sea level and also the sea level rise (SLR), through the analysis of a 2D numerical model results. The hydrodynamic features that were considered usefull to this study were the residual circulation, tidal asymmetry and tidal dissipation.

To reach these objectives, besides the hydrodynamic simulations, one salt marsh of each system was monitored during one year, and plant and sediment samples of *Spartina maritima* were colleted quaterly in order to determinate the vegetation coverage, above and belowground biomass, organic matter and sediment moisture. The model results suggest that the studied hydrodynamics parameters might explain the different characteristics of *S.maritima* found in the salt marshes, as a response to the difference hydrodynamic situations. Through the analysis of the model results, it was also intended to improve the knowledge about those hydrodynamic parameters in both systems and the possible effects of the SLR in their patterns. The SLR results indicate important differences, demonstrating how this estuaries hydrodynamics could evolve in case of sea level rising. Moreover, with the SLR and its effects in the hydrodynamic parameters, some abiotic features could be modified and, once salt marsh plants depend on them, their present status could be affected.

Contents

List of Figures

List of Tables

1. Introduction

1.1. Motivation and aims

Coastal regions are dynamic interface zones where land, water and atmosphere interact in a dynamic balance that is constantly being changed by natural and human influence. They represent extremely productive areas and accessible to people and, thus, are densely populated which intensify the anthropogenic pressures (Lopes *et al*., 2011b). Natural pressures are also being intensified as a result of climate change. An important consequence of climate change is sea level rise (SLR). Moreover, global mean sea level has been rising since the last century and it is expected to continue rising during the 21^{st} century at a higher rate (Lopes *et al*., 2011a). Therefore, studies considering the SLR scenario should be performed to predict its impacts on coastal areas.

The importance of the coastal systems such as estuaries and lagoons has been recognized a long time ago not only by the scientific community, but also by the populations who live around these areas (Vaz, 2007). As interface areas, these ecosystems are highly variable and rich, supporting important economical and social activities. As such, besides scientific motivations, estuaries and lagoons environments have an enormous historical importance, being fundamental for the human development. Thus, almost 60% of the most important cities in the world are located near or around this systems (Geophysics Study Commitee, 1997).

The scientific knowledge about these systems can be used to develop solutions to several problems such as the hydrographic basin's changes, the identification of sedimentation areas that can affect navigation, the computation of the residence time of substances within these areas, the study of water properties patterns to support aquaculture projects, among others (Vaz, 2007). In terms of estuarine hydrodynamics, tidal currents structure analysis is essential to understand problems such as dispersion, rate of pollutants, sediment transport and erosion processes (Prandle, 1982*)*. Moreover, tidal asymmetries and residual circulation have an influence on nutrient balances, sediment loads, particles and pollutants transportations, etc (Aldridge, 1997). Therefore, the understanding of the central processes lined by the tidal wave seemed to be crucial to obtain an overview concerning to the different uses of the coastal systems. As such, in the present work, one of the main goals is to evaluate the patterns of certain hydrodynamic features in two different estuaries and the possible effects of the SLR (an actual and important issue) in those features.

The coastal systems studied were Tagus estuary and Ria de Aveiro lagoon. Tagus estuary is located in the highest population density area of Portugal, crossing the capital Lisbon, is one of the largest estuaries of Europe and is the most extensive wetland area of portuguese territory (Dias, 1993). Likewise, Ria de Aveiro lagoon constitutes a very important area, being the most extensive shallow lagoon system in Portugal and the one most dynamic in terms of physical and biogeochemical processes (Picado *et al.*, 2010).

Both systems provides natural conditions for economic activities, like industry, navigation and recreation, enduring pressure from the large human population that inhabits its margins and depends upon its resources (Vaz, 2007; Araújo *et al.,* 2008). The Ria de Aveiro is classified under the Natura 2000 Network, being considered as a Special Protected Area (SPA), by the Birds Directive and by the Habitats Directive (Alves *et al.*, 2011). Tagus estuary is classified as a Natural Reserve since 1976 (Ramsar Convention on Wetlands) and is also classified as a Special Protection Zone for Wild Birds and a Site of Community Interest – Natura Network 2000 (Sumares, 2007). Both systems have extensive intertidal areas, including salt marshes, which provide an important service through the production of biomass. In fact, coastal ecosystems including salt marshes are among the most productive ecosystems of the biosphere (Vernberg , 1993; Mitsch and Gosselink, 2000; Lefeuvre *et al*., 2003; Sousa *et al.*, 2010b).

The vital importance of salt marshes is recognised worldwide in such a way they have been recently admitted in the Water Framework Directive (WFD). The biological productivity, hydrologic flux regulation, biogeochemical cycling of metals and nutrients and habitat for fish and wildlife, are among the several essential ecological functions (ecosystems services) supported by these ecosystems (Válega *et al.*, 2008). Salt marsh dynamics are the result of complex interactions among hydrodynamics, sediment transport and biology processes. There have been various attempts to develop a fuller understanding of the inter-relationship between physical and biological processes within salt marshes, but some physical and biological interacions as well as antropogenic effects or seal level rise are still subjects difficult to explain (Townend *et al.*, 2011). Futhermore, considering the importance of salt marsh and the possible effects of the global changes in this ecosystems, becomes important to know the present status of salt marshes, namely the role of the hydrodynamic parameters in its dynamics, and how their important services to the overall ecosystem will behave in a climate change scenario (Sousa *et al.*, 2010a). According to Sousa *et al*. (2010a), global climate change will affect salt marshes in terms of photosynthesis, growth, biomass allocation and nutrient uptake by plants and, consequently, salt marsh services are likely to be affected.

One of the main goals of this work is to evaluate the influence of the hydrodynamics patterns of Tagus estuary and Ria de Aveiro lagoon in their salt marsh dynamics, namely, in salt marsh plants, considering the actual sea level and also the sea level rise (SLR), through the analysis of numerical model results. The hydrodynamic features that were considered usefull to this study are the residual circulation, tidal asymmetry and tidal dissipation. To reach these objectives, besides the hydrodynamic simulations, one salt marsh of each system (Tagus estuary and Ria de Aveiro lagoon) was monitored during one year and plant and sediment samples of *Spartina maritima* were colleted quaterly in order to determinate the vegetaion coverage, above and belowground biomass, organic matter and sediment moisture.

Consequently, this work was motivated not only by the possibility to improve the knowledge about the residual circulation, tidal asymmetry and dissipation patterns in Tagus estuary and Ria de Aveiro lagoon and the possible effects of the SLR in their patterns, but also by the understanding of the effects of these hydrodynamic features in the salt marshes dynamics.

1.2. Structure of this work

For an overall understanding of the items studied and mentioned in this work, some of the main characteristics of estuaries and lagoons, of salt marshes, of the hydrodynamic features in study (residual circulation, tidal asymmetry and tidal dissipation) and of the actual concern about SLR are presented in this first chapter. Moreover, this chapter also includes the description of the main characteristics of the study areas in order to understand their principal morphologic and hydrodynamic features, as well as the state of the art of both systems, regarding mainly the hydrodynamic features in analysis. The state of the art of the numerical model used (Mohid) is also presented.

The second chapter describes the methodologies followed, which includes the field procedures and the consequently laboratory measurements regarding to the salt marsh plant in study, *S.maritima*. The numerical model, the simulations features and the hydrodynamic parameters calculations are also explained.

Model results and their discussion are presented in the third chapter. The residual circulation results are presented in first with the analysis of the different rivers discharges effects and also the impact of SLR in this parameter. The results and their interpretations for tidal asymmetry are next presented, following by tidal dissipation, including the results for actual and SLR scenarios. The results of the abiotic and biotic parameters for *S. maritima* evaluated in this work (sediment moisture, coverage area, ratio below/aboveground biomass and organic matter content) and the discussion of how can the hydrodynamic features help to explain the values founded represent the last issue of this chapter.

Finally, in chapter four are presented the most important ideas discussed in this work, as well as the main conclusions.

1.3. Estuaries and lagoons

According to Pritchard (1967), an estuary is defined as a half-closed water body which has a free connection with the open sea. In its interior, the salty water incoming from the ocean dilutes with the fresh water from the rivers. Frequently, the interaction can become more complex due to tidal action, whose amplitude varies as the tide spreads in the estuary. The water movements and the turbulent mixture that result from these forcing actions express problems and interesting challenges in the hydrodynamic field. Estuaries can be found under several forms and therefore their classification can include different types. However, all estuaries share common characteristics as result of being regions where salt water from the ocean and fresh water from rivers meet and interact (Miranda *et al*., 2002).

Coastal lagoons are semi-enclosed water bodies, characterized by small river flows and the influence of tides. These systems are typically shallow, with high salinities and may be enclosed by several barrier islands, as well as sand spits, or linked to the sea by one or more channels, which are small relative to the lagoon, like the Ria de Aveiro, located in northern Portugal (Barnes, 1980). Due to their narrow connection to the open ocean lagoons are, among other coastal systems, the most sensitive to human disturbances. Moreover, their restricted connections to the open sea, as well as the often partial stability of these inlets can disrupt the lagoons ecosystems, reducing the system's ability to flush exogenous substances leading to poor water renewal, eutrophication and other water quality problems. Besides, the low water renewal rates can also inhibit the function of the lagoons as nurseries. Hence, understanding water circulation within lagoons and their exchanges with the open sea becomes an important issue (Fortunato and Oliveira, 2005).

Furthermore, estuaries and lagoons constitute highly attractive places owing to their abundant natural and recreational resources, sheltered areas and/or beautiful landscapes. As ecosystems, estuaries and lagoons present many vital functions such being the natural habitat of birds, mammals and fish and the environment spawning and rearing of many biological communities. Moreover, these systems also play an important role in the migration routes of fish with commercial value (Ketchum, 1950). Therefore, estuaries and lagoons are known as areas with a large biodiversity and one of the most important ecosystems constituting these coastal areas are the salt marshes.

1.4. Salt marshes

Coastal ecosystems, including salt marshes found in estuaries and lagoons, are among the most productive ecosystems of the biosphere (Vernberg, 1993; McLusky and Elliot, 2004; Sousa *et al.*, 2010a). Likewise, salt marshes have multiple ecological and economic values as such these habitats are used for recreational and educational purposes by millions of people (Vernberg, 1993).

Salt marshes are coastal systems occupied by halophytic vegetation (plants adapted to coastal environments, being tolerant to salinity) exposed to low hydrodynamic conditions and tidal flooding (Simas *et al.*, 2001). Resulting from alluvial, sandy and muddy sediment deposits, those systems occur in coastal areas with low tidal fluxes, where the suspended sediments and debris deposition is possible. This process allows the mud banks formation which, in turn, allows the vegetation progress (Válega *et al.*, 2008). The characteristics of salt marshes are determined by a wide range of physical and biological controls and processes, including climate, shoreline configuration and wave climate, tidal range, sediment sources and volume of sediment input, sea level history and vegetation characteristics and dynamics (McLusky and Elliot, 2004; Van Proosdij *et al.*, 2006). They also depend on an adequate soil salinity and chemistry (Simas *et al.*, 2001).

Morphologically, salt marshes consist of a gently sloping vegetated platform, dissected by a network of tidal creeks that increase in width and depth seaward, presenting both vertically and horizontally grow. Salt marsh development is commonly pictured as beginning with the colonization of intertidal sand or mud flats by vascular plants that are both halophytic and tolerant of repeated submergence for periods of up to several hours. The establishment of plants then encourages the deposition of fine sediments and the accumulation of organic matter leading to the vertical growth of the developing marsh surface and the integration of the tidal creek network into the salt marsh (Davidson-Arnott *et al.*, 2002).

Salt marsh vegetation is usually divided into a low marsh community, which is often dominated by a single species such as *Spartina maritima*, and a more diverse high marsh community, which grades into upland plant communities. Vegetation growth occurs down to about the mean tide level. Plants in the low marsh are subject to inundation by almost every tide and during six or more hours. High marsh plants may only be submerged for brief periods during spring tides or at the upper end only a few times a year during extreme astronomical tides and/or storm surges (Davidson-Arnott *et al.*, 2002). Therefore, salt marsh halophyte communities are spatially distributed according to the marsh's topography, which determines the frequency and duration of tidal submersion, the physical and chemical characteristics of the sediment and the interspecific competition conditions (Sousa *et al*., 2010a).

As result of the water, sediment and vegetation interactions, salt marshes present a dynamic nature, having a wide geographical distribution (Válega, 2009), colonizing the upper intertidal zones in latitudes ranging from the Arctic to the subtropics, including back barrier lagoons and bays, river mouths, estuaries and deltas, natural embayments and sheltered areas. They may also develop on open coasts where wave energy is dissipated over a wide and shallow nearshore (Davidson-Arnott *et al.*, 2002). Tidal amplitude, in relation to slope and elevation of the shore, is a determining factor for the location of salt marshes once they are located in areas receiving both inundation by sea water and exposure to air. In fact, tidal range and the tidal regime (semidiurnal, mixed or diurnal) influence the hydrodynamics of flow in tidal creeks and over the marsh surface, as well as the extent and duration of inundation, which influence the vertical and horizontal extent over which salt marsh development takes place (McLusky and Elliot, 2004; Davidson-Arnott *et al.*, 2002).

By occupying zones of transition between terrestrial and marine ecosystems, marshes play a critical role in sediment exchange with adjacent mud flats and open coastal waters, acting as sinks for fine sediments and for the accumulation of organic matters (Davidson-Arnott *et al.*, 2002).

Ecologically, salt marshes are generally areas of high primary productivity and species diversity, representing habitat for migratory waterfowl, transient fish species and indigenous flora and fauna (Simas *et al.*, 2001; McLusky and Elliot, 2004). The export of organic matter from the marsh is an important component of the food chain of the adjacent coastal waters and mud flats, ultimately supporting large populations of finfish and shellfish. Salt marshes also provide staging and wintering habitats for a wide variety of shorebirds and waterfowl (Davidson-Arnott *et al.*, 2002). Moreover, commercially, these ecosystems provide important resources as nursery grounds for several fish and crustacean fisheries (Simas *et al.*, 2001).

Salt marsh plants provide an important service through the production of biomass, contributing to a greater stability and lower erosion of the coastal areas and increasing pollution retention (Vernberg, 1993; McLusky and Elliot, 2004). Moreover, nitrogen and phosphorous uptake from sediment interstitial waters and their incorporation in this plant biomass leads to the nutrient sequestration and retention, thus decreasing its availability in the water column and potentially reducing eutrophication. Furthermore, carbon fixation by photosynthesis in salt marshes helps decrease atmospheric CO_2, which in turn contributes to ecosystem health (Sousa *et al*., 2010a).

In warm-temperate estuaries, such as Tagus estuary and Ria de Aveiro lagoon, salt marshes are often colonized by the halophytes *Spartina maritima*, *Scirpus maritimus*, *Halimione portulacoides*, *Sarcocornia fruticosa* and *Sarcocornia perennis* (Sousa *et al.*, 2010a).

After the recognition of this ecological significance, the potential threats to marshes by human activities become a concern. Halophyte vegetation is responsible for the majority of the wave energy dissipation found in these environments, providing a form of sea defence, reducing the need of sea walls or dikes to protect the hinterland (Townend *et al.* 2011). However, salt marsh vegetation is very sensitive to the inundation frequency (Suchrow and Jensen, 2010). In fact, it is expected that changes in relative sea level play an important role in the development, maintenance and long-term health of salt marshes (Kolker *et al*., 2008).

1.5. Hydrodynamic parameters

1.5.1. Residual circulation

In coastal systems, the sediment transport is a long-term process dependent on linear interactions between flow and bathymetry. Long-term residual currents play an important role in the transport of sediment, nutrients and organic matter from lagoons and estuaries, namely, their exportation toward coastal seas or their retention inside the water bodies. In these systems, residual transport and circulation are essentially dominated by tidal asymmetries, although rivers and wind influence are also important. Bottom friction effects and vorticity advection also induced residual circulation (Lopes and Dias, 2011).

Because of the nonlinearity of these processes, numerical models have been found to be an appropriate tool to investigate the tidal and residual flow in several systems, as for instance in the Gulf of California (Dworak and Gómes-Valdés, 2002), Shark Bay in the Western Australia (Burling *et al.,* 2003) and in the Ria de Aveiro in Portugal (Sousa and Dias, 2007; Lopes and Dias, 2011).

1.5.2. Tidal asymmetry

A symmetrical tide occurs when the rise and fall of the tide have identical duration, with approximately equal maximum velocities attained, resulting in no net overall sediment transport. Tidal asymmetry happens when the ebb and flood durations are unequal and is caused by tidal wave distortion during propagation into shallow water, along the coastal shelf and on entry into shallow water systems. This phenomenon is ruled by the mechanism of the nonlinear effect of tidal propagation. As the tidal wave approaches the coast, it is travelling as a shallow water wave and therefore, the phase speed is proportional to the square root of the water depth and the crest travels faster than the trough due to the greater water depth under the crest. Consequently, information of tidal asymmetry may become very useful to determine the patterns of currents, including the prevalence of current flood or ebb (Sivakholundu *et al.*, 2006). For instance, the navigability of the estuarine channels and estuaries geological evolution are affected by tidal asymmetry (Aubrey and Speer, 1985) which is, therefore, a fundamental factor for morphological development in tidal basins.

Tidal asymmetry has important implications for estuarine sediment transport, water contaminants dispersal and, on geological time scales, estuarine stability (Aubrey and Speer, 1985; Pugh, 2004). Flood dominant estuaries tend to accumulate coarse sediments in their channels whereas ebb dominant estuaries tend to flush seaward the near-bed sediments. Friedrichs and Aubrey (1994) referred that tidal distortion in shallow estuaries can be the result of two effects: frictional interaction of the tide with the bottom and storage of water on intertidal flats and saltmarshes. These authors concluded that the ratio M_4/M_2 is primarily controlled by the first effect in flood dominant estuaries and by the second effect in ebb dominant estuaries.

1.5.3. Tidal dissipation

According to Dias (1993), the values of the average rate of energy dissipation arise, in general, associated with areas where the boundary friction is high or where a sudden change of estuary geometry occurs. Thus, changes in estuary bathymetry and geometry could have a substantial effect in the way that the tidal wave energy is dissipated and may even be responsible for the tidal wave distortion.

1.6. Sea level rise

Sea level change is an important consequence of climate change due to its impact on society and ecosystems. The anthropogenic pressures in coastal zones are being intensified as a result of climate change (Lopes *et al.*, 2011a). Several studies such the one performed by Church and White (2006) reveal that global mean sea level has been rising during the 20th century at a rate of 1.7 ± 0.5 mm/year and it is expected to continue rising during the 21st century at an increasing rate. In fact, for the 21st century, Meehl *et al.* (2007), for example, indicates a global rise ranging between 0.18 and 0.59 m and a higher rise was predicted by Rahmstorf (2007), between 0.5 and 1.4 m.

Various causes are associated to mean sea level change: thermal expansion, related with the reaction of the ocean to global atmospheric temperature rise; mass exchange due to the melting of mountain glaciers and ice caps and changes in Greenland and Antarctic ice sheets; dynamic changes as a consequence of density gradients; land subsidence, that is, the vertical movements in the solid earth associated to tectonics and isostatic adjustment (Chao *et al.*, 2002). While some of these causes have global effects, long-term dynamic changes and land subsidence affect mean sea level locally. Hence, the sea level is not changing uniformly around the world. The response of each coastal region to SLR depends on the physical features of the coastal system and on the rate of local relative SLR. Thus, the effects of SLR should be evaluated locally in order to improve the tools for vulnerability assessment (Lopes *et al*., 2011a).

Regarding to Portuguese coast, the areas that will probably be the most affected by an accelerated SLR are the Ria de Aveiro and the Ria Formosa lagoons and the Tagus and Sado estuaries (Lopes *et al*., 2011a). Lately, Lopes *et al.* (2011a) projected the local mean sea level change for Portuguese coast for the period 2091–2100 relative to 1980–1999. The future climates were simulated imposing different emission scenarios of greenhouse gases developed by Intergovernmental Panel on Climate Change (IPCC) and three scenarios of the Special Report on Emission Scenarios (SRES) were considered, based on a range of possible behaviours of society, economy and technology. These projections revealed an increase in the mean sea level of 0.35 m, 0.28 m and 0.42 m. In the present work, in order to evaluate the impact of sea level rise in some hydrodynamic features of Ria de Aveiro and Tagus estuary, only the worst scenario is considered (0.42 m) because it has the highest potential impacts in coastal regions, as referred by Lopes *et al.* (2011a).

1.7. Study areas

The main characteristics of Tagus estuary and the Ria de Aveiro lagoon, namely their morphology and hydrodynamic features, are presented in the present section.

Figure 1 indicates the salt marshes studied in the present work, which location is indicate by the arrows. The salt marshes studied in Ria de Aveiro and Tagus estuary are called Barra salt marsh and Rosário salt marsh, respectively.

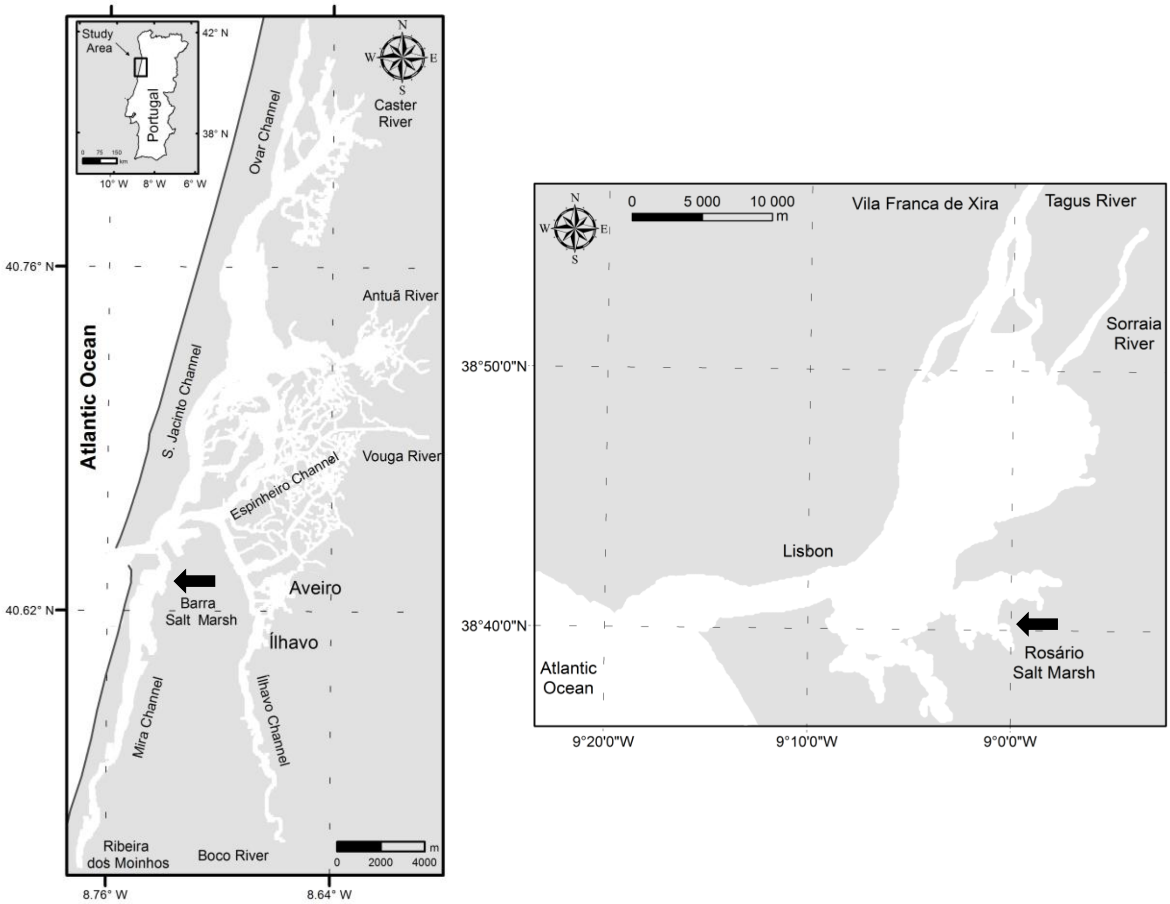

Figure 1: Ria de Aveiro lagoon (left) and Tagus estuary (right). The arrows indicate the salt marsh areas analysed in this work (arrow on the left: Barra salt marsh, in Ria de Aveiro lagoon; arrow on the right: Rosário salt marsh, in Tagus estuary).

1.7.1. Tagus estuary

The Tagus estuary (Fig.1) is one of the largest estuaries of the west coast of Europe and is located in the most populated area of Portugal, including the capital Lisbon. The estuary occupies a mean volume of 1900 ×10^6 m^3 and a surface area of about 320 km^2 (Valente and Silva, 2009).

According to Gameiro *et al.* (2007) Tagus estuary presents a large diversity of resident and migratory fishes and constitutes the natural habitat for a large resident and migratory bird population. Several groups of primary producers can be found in the estuary ecosystem. Although diatoms are the predominant group, other relevant primary producers can be found, namely, microphytobenthos.

1.7.1.1. Morphology

Tagus estuary width varies between 2 and 15 km, it has an average depth of 10.6 m and can be divided in two distinct regions, the lower and the upper estuary, that present different morphologies and properties. The lower estuary connects with the Atlantic Ocean and is a channel of about 30 m depth, 2 km of width and 12 km length that opens in a large bay (upper estuary) on the east side. The upper estuary (also called bay), extending from Vila Franca de Xira to the end of the main channel (Fig.1), is wide (more than 10 km in some places) and shallow (15 m of maximum depth) and is characterized by extensive zones of tidal flats and salt marshes, small islands and a net of narrow channels, sometimes only ten meters width (Dias and Valentim, 2011; Fortunato *et al.*, 1997).

About 40% of the estuary's total area is tidal flats (Fortunato *et al.*, 1999) which is an important feature of many estuaries from varied point of view. For example, at the physical level, they slow the tidal propagation and dissipate large amount of tidal energy or, from an ecological perspective, they contribute significantly to primary production. In fact, tidal flats effects on hydrodynamics can have repercussions on the ecosystem and inclusively affects biological cycles (Dias and Valentim, 2011).

1.7.1.2. Hydrodynamic features

The hydrography of the estuary is modulated by the tidal propagation and fluvial discharge from the major rivers, Tagus, Sorraia and Trancão. In general, the system is well-mixed and has an average tidal prism of 600×10^6 m^3 (Vaz *et al.*, 2011).

Tagus is a mesotidal estuary and tides are semi-diurnal. According to Fortunato *et al.* (1999), M_2 is the dominant tidal constituent with amplitudes of the order of 1 m. The tidal range within the estuary varies from 0.8 m (neap tide) to 4.0 m (spring tide) and increases towards the estuary's interior (Portela and Neves, 1994; Fortunato *et al.,* 1997). More precisely, the amplitudes of astronomic constituents grow rapidly in the lower estuary and more steadily in the upper estuary and then decrease up to Vila Franca de Xira (Fortunato *et al.*, 1999).

Tagus is ebb dominated, with floods typically one hour longer than ebbs, and this behaviour leads to stronger velocities during ebbs, and thus to a net export of sediments. However, there is a reduction of the sediment flux into the shelf, which could be partially responsible for both the erosion at the mouth of the estuary, and the accretion in the upper estuary (Fortunato *et al.*, 1999). The area affected by tides reaches 80 km landward of Lisbon and the maximum current speed induced by the tides is around 2.0 ms^{-1} (Gameiro *et al.*, 2007).

According to Oliveira (1993), the tidal amplitude inside the Tagus estuary is larger than offshore as a result of a small resonance effect, and therefore this estuary can be hydrodynamically interpreted as a greater tidal basin connected to the ocean by a relatively straight and narrow channel. Other authors also mentioned this effect, such as Neves (2010) and Fortunato *et al.* (1997), for example. The last one refers that tidal form number decrease along the system due to a resonant mode that increases the amplitudes of semi-diurnal waves by roughly 40% in the upper estuary, leaving the diurnal waves mostly unchanged.

The major source of freshwater is the Tagus river and the discharge usually shows a pronounced dry/wet season signal and a large inter-annual (Valente and Silva, 2009). The annual average flow is approximately 400 m^3/s, but varies greatly from summer to winter between approximately 30 m^3/s in a dry summer and 2000 m^3/s in a wet winter (Neves, 2010). Other freshwater inputs to the estuary, the Sorraia and Trancão rivers, are comparatively small, with average annual discharges of about 35 and 2.5 m^3s^{-1}, respectively (Neves, 2010).

The influence of the river discharge seasonal variability is evidenced by several estimates for the water residence time within the Tagus estuary (Neves, 2010). For example, Martins *et al.* (1983) reported a residence time between 6 and 65 days, respectively, for a river discharge between 2200 and 100 m^3s^{-1}, and 23 days for a mean river discharge of 350 m^3s^{-1}.

Tagus river is the highest nutrient source to the estuary, although Sorraia and Trancão rivers also represent significant nutrient contributions to the system. Salt marshes areas also function as nutrient source mostly in summer (Cabeçadas *et al*., 2000). The estuary also receives effluent discharges, mainly from several urban, industrial and agricultural sources (Vaz *et al.*, 2011).

The wind regime in the region exhibits a marked seasonal pattern, presenting south southwest predominant winds during the wet seasons, rotating to north/northwest during the dry season (Vaz *et al.*, 2011).

1.7.1.3. Rosário salt marsh

According to Caçador *et al.* (2009), about 40% of the Tagus estuary is composed of intertidal mudflats and the southern and eastern shores contain extensive areas of salt marshes colonized mainly by *S. fruticosa*, *S. perennis*, *H. portulacoides* and *S. maritima*. Within the estuary, salt marshes occupy approximately 20 km^2 (ca. 6%) (Pedro *et al*., 2008).

According to Simas and Ferreira (2007) and Sousa *et al.* (2010b), in Tagus estuary, salt marsh plants are responsible for 25% of the total primary production. Nevertheless, only a small fraction of the produced biomass is accumulated within the marsh since the majority is exported to other areas of the system, to adjacent coastal waters or can also be degraded.

Rosário salt marsh, covering an area of 200 ha, is located in the southern shoreline of the Tagus estuary (Fig. 1) and is characterized by a typical zonation with homogeneous stands of *S. maritima* as a pioneer species, colonizing bare mud in the lower marsh area. Pure stands of *H. portulacoides* follow *S. maritima* while *S. fruticosa* and *S. perennis* are found in the upper salt marsh. This marsh is fully inundated twice a day by tidal action through a highly branched system of channels. These channels have 0.5–1.5 m depth which promotes the inundation of the higher marsh even at low amplitude tides (Caçador *et al*., 2009).

1.7.2. Ria de Aveiro lagoon

The Ria de Aveiro (Fig. 1) constitutes a very important coastal system in the Portuguese west coast. Covering an area of 83 km^2 at high tide (spring tide) and 66 km^2 at low tide (Dias and Lopes, 2006), it is the most extensive Portuguese lagoon system and the one most dynamic in terms of physical and biogeochemical processes (Picado *et al.*, 2010).

Biologically, it is considered rich in nutrients and organic matter and is, therefore, a highly productive environment, providing a habitat for birds and several commercially important fish and invertebrate species (Araújo *et al.*, 2008).

1.7.2.1. Morphology

The lagoon is 45 km long, 10 km wide and is connected to the sea by a 350 m wide inlet, fixed by two jetties (Picado *et al.*, 2010). Four main branches radiate from this sea entrance: Mira, S. Jacinto, Ílhavo and Espinheiro channels. The Mira channel is an elongated shallow arm presenting 20 km length, S. Jacinto channel is about 29 km long and Ílhavo and Espinheiro are 15 and 17 km long, respectively (Dias, 2001). Mira and Ílhavo channels are located in the southern region, S. Jacinto channel, in its northern region, and the Espinheiro channel, in a very complex central area of the lagoon. Therefore, the system is characterized by a large number of channels between which lie significant intertidal areas, essentially mudflats, salt marshes and old salt pans (Picado *et al.*, 2010).

Hydrologically, each of the main channels present features of separate estuaries, providing typical salinity and water temperature estuarine longitudinal gradients, with values close to the characteristics of the oceanic water near to the inlet and close to freshwater furthest upstream (Dias *et al.*, 1999).

The average depth of the lagoon relative to the mean sea level is about 3 m although the inlet channel can exceed 28 m deep, due to dredging operations that are frequently carried out to allow the navigation. Due to the small depth and to the significant tidal amplitude there are zones, especially along the borders of the lagoon and in its central area, which are alternately wetted and dried during each tidal cycle (Picado *et al.*, 2010).

1.7.2.2. Hydrodynamic features

The lagoon receives sediments and freshwater of several small streams and several rivers. The major fluvial input comes from the Vouga (50 m^{3}s^{-1} average flow), which is responsible for about 66% of the freshwater input in the lagoon, and Antuã rivers (5 m^{3}s^{-1} average flow) and the total mean estimated freshwater input is approximately 1.8x10^6 m^3 during a tidal cycle (Moreira *et al.*, 1993). The tidal prism of the lagoon for maximum spring tide and minimum neap tide is estimated as 136.7x10^6 m^3 and 34.9x10^6 m^3, respectively (Dias, 2001). Hence, the total mean estimated freshwater input is very small (2.5%), when compared to the mean tidal prism at the mouth (approximately 70x10^6 m^3) (Picado *et al.*, 2010).

In Ria de Aveiro lagoon tides are predominantly semidiurnal with a mean tidal range of about 2.0 m, mainly influenced by the lunar semi-diurnal constituent (M_2), with 88% of the total tidal energy (Dias *et al.*, 1999). The minimum tidal range is 0.6 m (neap tides), and the maximum tidal range is about 3.2 m (spring tides), corresponding to a maximum and a minimum water level of 3.5 and 0.3 m, respectively (Dias *et al.*, 2000). The strongest currents are observed at the inlet channel, reaching values higher than 2 ms^{-1} (Vaz *et al.*, 2009a).

Dias (2001) and Lopes *et al.* (2006) characterized the first half of the main channels of the Ria de Aveiro lagoon as ebb dominant and the second half as flood dominant. The ratio between the amplitudes of the M_4 and the M_2, regarded as a measure of tidal asymmetry, is very small near the lagoon mouth increasing along the channels (Picado *et al.*, 2010).

Wind is very significant in Aveiro considering periods from a few hours to a few days, when can become an important influence on lagoon circulation. Extreme conditions of strong wind may induce particular circulation patterns mainly in shallow areas and wide channels (Dias, 2001).

The evolution of the Ria de Aveiro during the 20th century has been characterized by the erosion of these intertidal areas and widening of most channels. These changes, together with other anthropogenic contributions, are believed to have modified the tidal dynamics of the system, making it more vulnerable to risks of flooding and to sea level rise (Silva and Duck, 2001).

1.7.2.3. Barra salt marsh

The salt marshes of the lagoon are mainly vegetated by *H. portulacoides*, *S. perennis* subsp. *perennis*, *S. ramosissima*, *Puccinellia maritima*, *Juncus maritimus* and *Triglochin maritima,* as referred in the studies performed by Silva *et al.* (2007, 2009).

The Barra salt marsh (Fig. 1), located in the mid-low salt marsh near to a main channel of the lagoon (Mira Channel), occupies about 2.2 vegetated hectares and is inundated twice a day by the tide (Silva *et al.*, 2009). The salt marsh vegetation found in these salt marshes is dominated by *Spartina maritima*, *Halimione portucaloides*, *Juncus maritimus* and *Sarcocornia perennis* subsp. perennis.

1.8. State of the art

The importance of coastal environments is recognized all around the world by the scientific community. Consequently, numerous studies of estuaries were published focusing on their hydrology, biology and ecological classification, hydrodynamic features, etc. In this section are referred a few examples of the numerous studies that have been performed in the study areas of the present work and are also referred some of the most import studies performed by the application of the model Mohid, once it is the numerical tool used in this study.

1.8.1. Tagus estuary

In Tagus estuary, according to Rodrigues da Silva (2003), the first important study was the one performed by Baldaque da Silva (1893), motivated by the need to assure the easy and safe navigability within the system. The first integrated study on this estuary was carried out by Arantes and Oliveira (1941), who analysed the hydrodynamic and salinity distribution processes and the water quality. These two studies are worth mentioning due to their historical importance.

Studies on biological parameters such the work developed by Costa (1986) showed the importance of the estuary as a nursery for some fish species with economic importance. The impact of pollution caused by mercury, for example, was also analysed in studies performed by Canário *et al.* (2005, 2010), for example. These and several other projects have been carried out on the Tagus estuary, using *in situ* measurements, physical and numerical modelling or remote detection, which resulted on publications in different areas such as: development of numerical models (e.g. Rodrigues *et al.,* 1986; Âmbar and Backhaus, 1983); morphodynamics (e.g. Freire *et al.,* 2006); suspended sediments (e.g. Vale and Sundby, 1987; Portela and Neves, 1994) hydrodynamics (e.g. Fiadeiro, 1987; Dias, 1993; Vaz *et al.*, 2011); circulation and tidal propagation (e.g. Fortunato *et al.*, 1997, 1999; Dias and Valentim, 2011); monitoring and operational modelling (e.g. Anjos *et al.,* 2003; Fernandes *et al*., 2004); estuarine plume (e.g. Valente and Silva, 2009; Vaz *et al*., 2009b); phytoplankton (e.g. Gameiro *et al*., 2007), and so on.

Despite all these examples of studies development concerning Tagus estuary, the amount of work dedicated recently to its hydrodynamics is limited (Dias and Valentim, 2011). Dias (1993) performed the deepest study on the Tagus estuary hydrodynamics and the most significant work was developed by Fortunato *et al.* (1997) concerning the numerical study of the 3-dimensional currents at the mouth of the estuary.

Recently, Neves (2010) analysed the results of several monitoring programmes performed along the Tagus estuary, studying its dynamics and hydrology. Their results indicate that the Tagus dynamics and hydrology is strongly dependent on the tidal forcing and seasonal changes of the river inflow. The author also conclude that the fortnightly cycle was the main forcing mechanism for the residual circulation, but the bottom topography and the coastline morphology play an important role on the estuarine circulation, complementing the fortnightly tide on the establishment of different residual circulation patterns. Similarly, in the study performed by Dias and Valentim (2011), tidal propagation within the system was resolved through the application of a 2D model and the results showed that the tidal dynamics of Tagus estuary is extremely dependent on the estuarine topography and coastline geometry, resulting essentially from a balance between convergence/divergence and bottom friction effects.

Regarding to tidal asymmetry, Dias (1993), Fortunato *et al.* (1999) and Neves (2010) noticed that this system is dominated by the ebb. The existence of asymmetry in the tide within the Tagus estuary is evidenced by ebbs being shorter than floods.

Therefore, the Tagus estuary has been widely studied but there are still many aspects that need additional clarification and, for example, the relation between estuary's circulation and its main forcing mechanisms (tide, wind and river discharge) can still be further investigated (Neves, 2010). Likewise, Tagus salt marshes have been studied in the last years and a significant amount of work was dedicated to the nutrient cycling (e.g. Sousa *et al.* 2008a,b) or metal retention (e.g, Caçador *et al.,* 2009; Duarte *et al.*, 2010), but studies devoted to the hydrodynamic features that could affect salt marsh plants are rare.

1.8.2. Ria de Aveiro lagoon

Ria de Aveiro lagoon was largely studied from a biological and chemical perspective and several publications regarding to bacterioplancton, zooplankton, benthic biodiversity, pollution impacts, fisheries, among several others issues were performed (e.g. Morgado *et al.*, 2003; Lopes *et al.*, 2010; Anjum *et al.*, 2012; Pereira *et al.*, 2011; Pires *et al.*, 2012; Ahmad *et al*., 2012).

Like in the case of Tagus estuary, Ria de Aveiro salt marshes have been studied in the last years. A substantial amount of work was dedicated to the nutrients cycling (e.g. Lillebø *et al.*, 2010) and metal contamination (Válega *et al*., 2008; Marques *et al.*, 2011; Sousa *et al.,* 2011) . Silva *et al.* (2009), studying salt marshes in Tagus estuary and Ria de Aveiro lagoon, demonstrate that the type of salt marsh surface coverage is not the main factor that contributes to the consolidation of sediments and the position of stations (species/unvegetated areas) and related abiotic conditions are determining factors of variation to take into account in the studies related with the stabilization and survival of salt marshes. Silva *et al.* (2007) evaluated aspects of population dynamics and salinity tolerance of the salt marsh plant *Salicornia ramosissima* in two salt marshes of Ria de Aveiro lagoon. However, once again, studies devoted to the hydrodynamic features that could affect salt marsh plants are not so commun.

Over the last years, Ria de Aveiro hydrodynamics has been studied using several model implementations and distinct parameters were analysed. Several studies were performed to investigate matters such as the tidal propagation in the lagoon (Dias *et al*., 2000; Dias and Fernandes, 2006) and, for example, Dias *et al*. (2000) pointing out that the tidal amplitude decreases at the upstream locations, while the phase lag in the high and low water increases. The Lagrangian transport of particles (Dias *et al*., 2001) and the sediment transport (Dias *et al*., 2003; Lopes *et al*., 2006, 2011b) are also issues analysed. Vaz *et al*. (2005), combining field measurements and modelling results, revealed the importance of the river flow in the establishment of the thermohaline horizontal patterns in the central area of the lagoon. Moreover, Vaz *et al*. (2005; 2007) implemented the Mohid-2D in order to evaluate the role of the major forcings (tides and river inflow) in the hydrodynamics and hydrographic features of the central area of the Ria de Aveiro. Picado *et al.* (2010) investigated the possible tidal changes induced by local geomorphologic modifications such as the total degradation of the abandoned salt pans within the Ria de Aveiro lagoon. A 3D baroclinic model (Mohid) was used by Vaz *et al*. (2009a) and Vaz and Dias (2011) to perform simulations for the Espinheiro channel in Ria de Aveiro. All of these studies are just some examples of the large number of works developed in the last years concerning the different approaches of the lagoon's hydrodynamics.

Regarding to lagoon hydrodynamics, a prior study evaluated by Dias *et al*. (1999) reveals some of the main features of the Ria de Aveiro like the tidal wave propagation in the lagoon that has the characteristics of a damped progressive wave or the vertically homogeneous features of this lagoon. Araújo (2005) has analysed sea level changes in Ria de Aveiro lagoon and has concluded that there was a general increase in the amplitude and a phase decrease, for most of harmonic constituents.

Concerning the residual circulation Dias (2001) and Lopes and Dias (2007), through the application of a hydrodynamic model, conclude that residual currents and transport are stronger at S. Jacinto and Espinheiro channels (Fig.2), as well as at the lagoon mouth (Barra), and are directed downstream toward the open ocean, contributing to net water and particles exports. The residual circulation induced by river freshwater inputs may experience an important increase during the rainfall season, due to the increase of the input from the main freshwater tributaries, influencing therefore, the lagoon channels dynamics. These authors referred that the residual circulation pattern in Ria de Aveiro lagoon evolves continually in time, as result of the bottom sediment dynamics and of the anthropogenic activities related to the dredging operation in several channels, as well as the exploitation of the lagoon sediments. Once, the bottom topography evaluation is crucial to the long-terms dynamic studies in lagoons and estuaries. Also, the flooding-drying process over the intertidal areas tends to enhance the asymmetry of tidal currents over a tidal cycle, during the spring–neap cycle, resulting in a relatively large residual flow along the estuary. This mechanism amplifies the tidal asymmetries inside the lagoon, enhancing the residual currents. The neap–spring cycle may, therefore, play an important role in the long-term sediment transport in the central areas of the lagoon. In these areas, the residence time is small and the ebb currents are strong, resulting in a residual transport toward the lagoon mouth.

Likewise, Dias (2001), Lopes *et al.* (2006) and Araújo *et al.* (2008) characterized the first half of the main channels of the Ria de Aveiro lagoon as ebb dominant and the second half as flood dominant. All these studies show that the ratio between the amplitudes of the M_4 and the M_2, considered as a measure of tidal asymmetry, is very small near the lagoon mouth increasing along the channels (Picado *et al.,* 2010).

1.8.3. Numerical model

In this work was used the numerical model Mohid – Water Modelling System, originally developed by the MARETEC – Marine and Environmental Technology Center group of the Instituto Superior Técnico (Martins *et al*., 1998). Mohid is a 3D baroclinic finite volume marine model, designed for coastal and estuarine shallow water applications (Vaz, 2007), like the study of Ria de Aveiro and Tagus estuary dynamics.

Mohid has been applied to different coastal and estuarine areas, showing its capability to simulate complex flows features. In Portugal, numerous estuarine systems have been studied such as:

- Douro (Silva, 1996) and Mondego rivers (Saraiva *et al*., 2007)
- Ria de Aveiro lagoon (Trancoso *et al*., 2005; Vaz *et al*., 2005, 2007)
- Óbidos lagoon (Santos *et al*., 2006; Malhadas *et al*., 2009)
- Ria Formosa lagoon (Silva *et al*., 2002)
- Tagus estuary (Braunschweig *et al*., 2003; Vaz *et al*., 2009b, 2011)
- Sado estuary (Martins *et al*., 2001)
- Guadiana estuary (Saraiva *et al*., 2007)

Moreover, Mohid has been implemented in other Iberian Peninsula systems such in the Galician Rias (i.e. Villarreal *et al*., 2002; Taboada *et al*., 1998; Montero, 1999) and also in open sea: on the Iberian Coast, including the Portuguese coastal circulation (Coelho *et al.,* 2002), slope Cantabrian current (Villarreal *et al*., 2004), Algarve coastal circulation (Leitão *et al*., 2005) and on the North Sea (Bernardes, 2007).

All this extensive number of studies in several coastal environments with different resolutions indicates that the numerical model Mohid has capabilities to simulate the hydrodynamics of coastal systems such Ria de Aveiro lagoon and Tagus estuary.

2. Methodology

2.1 Salt marsh field measurements and laboratory analysis

S.maritima is an herbaceous perennial plant distributed along the coasts of western, southern, and south-eastern Europe, and western Africa. This species colonizes low marshes (Sousa *et al*., 2010a). In this study, *S.maritima* is the salt marsh plant analysed because is present in both salt marshes of the two estuaries and is a pionner spicies, which means that colonizes the low salt marsh (Sousa *et al.*, 2010a) and, therefore, is the species that is closest to the water.

The percentage vegetation coverage, above and belowground biomass, sediment moisture and organic matter sediment content was determined for Rosário and Barra salt marshes through the application of the following steps that includes the field and further laboratory measurements:

► **Above and belowground biomass determination** (based on Reboreda and Caçador (2007))

- *S. maritima* was sampled at low tide quarterly during one year, from January 2010 to December 2011;
- Specimens were collected in the salt marsh, in three different places in pure stands of *S.maritima*, chosen randomly;
- The aboveground material was determined by clipping the vegetation at ground level in 0.3 x 0.3 m^2 squares (three replicates);
- After cutting the aboveground material and removing the detritus, one sediment core was taken in the three places where the aboveground biomass had been collected using a tube with 7 cm diameter and 100 cm length;
- The belowground biomass was sorted out from the sediment cores to a depth of 40 cm, where the roots and rhizomes are present;
- The collected aboveground plant material was transported to the laboratory, rinsed with demineralised water and dried to constant weight at 80ºC;
- Belowground material was separated from the sediment using a 250 µm mesh sieve and demineralised water; the remaining plant material was dried to constant weight at 80ºC;
- After this steps, plant material was weight with an accuracy of 0.01 g and the biomass was expressed as $kg.m^{-2}$ through the following equations:

$$\text{Aboveground biomass } (\text{Kg.m}^{-2}) = \frac{\text{Collected Biomass}}{0.090\ (\text{m}^{-2})} \qquad (1)$$

$$\text{Belowground biomass (Kg.m}^{-2}) = \frac{\text{Collected Biomass}}{\pi r^2} \qquad (2)$$

where r=0.07 m (core radius)

► **Organic matter and relative moisture** (based in Duarte *et al.* (2010))

- Relative moisture of the sediment between roots and rhizomes was determined and expressed as percentage of total weight;
- Approximately 2 g of the sediment was dried at 60°C for 72 h and the moisture was calculated by the application of the next equation:

$$\text{Moisture (\%)} = \frac{\text{Fresh weight} - \text{Dried weight}}{\text{Fresh weight}} \times 100 \qquad (3)$$

- The dried sediment was grinding and sieving for removing organic waste (branches, roots, fauna). In order to determine the organic matter, 0.5 g of sediment was placed in a previously weigh crucible;
- After incineration at 600°C during 3 h, the crucible was transferred to a desiccator for cool down;
- Then, the crucible with the incinerated sediment was weigh and organic matter was determined using the formula:

$$\text{Organic Matter (\%)} = \frac{(\text{Sediment weight}+\text{Crucible weight}) - (\text{Incinerated sediment weight}+\text{ Crucible weight})}{(\text{Sediment weight}+\text{Crucible weight})} \times 100 \qquad (4)$$

► **Vegetation coverage area** (based on Caçador *et al*. (2004))

- A transect 130 m long and 1 m wide was established perpendicular to the channel in order to represent the main vegetation areas in the salt marshes;
- Sampling was conducted quarterly between January 2010 to December 2011;

- Floristic composition and species abundance were determined based on visual estimation of species cover using the *Braun Blanquet* abundance scale. For the present work only the coverage percentage of *S. maritima* was considered.

These procedures have been performed in Rosário salt marsh by Bernardo Duarte, from the Oceanographic Institute (Lisbon). The sampling results for Rosário salt marsh were then kindly provided in order to reach the objectives of this thesis.

2.2. Numerical model

A mathematical model can be considered as an approximate reconstruction of a real phenomenon, but all parameterizations and approximations used in models lead to deviations of the model results from nature. Nowadays, two-dimensional vertically integrated (2DH) models can be considered as reliable tools for the study of shallow coastal waters (Dias *et al*., 2003). In this work, the Mohid-2D model, previously successfully calibrated and implemented for Tagus estuary (Vaz *et al*., 2011) and Ria de Aveiro lagoon (Vaz *et al*., 2007) was applied.

2.2.1. The numerical model equations

Mohid solves the three-dimensional incompressible primitive equations. Hydrostatic equilibrium is assumed as well as the Boussinesq and Reynolds approximations. A detailed derivation of the model equations was presented in several studies and can be consulted in Vaz (2007), for example.

The momentum and mass balance equations are:

$$\frac{\partial u_i}{\partial t}+\frac{\partial (u_i u_j)}{\partial x_j}=-\frac{1}{\rho_0}\frac{\partial p_{atm}}{\partial x_i}-g\frac{\rho(\eta)}{\rho_0}\frac{\partial \eta}{\partial x_i}-\frac{g}{\rho_0}\int_{x_3}^{\eta}\frac{\partial \rho'}{\partial x_i}dx_3+\frac{\partial}{\partial x_j}\left(v\frac{\partial u_i}{\partial x_j}\right)-2\varepsilon_{ijk}\,\Omega_j\,u_k \quad (5)$$

$$\frac{\partial u_1}{\partial x_1}+\frac{\partial u_2}{\partial x_2}+\frac{\partial u_3}{\partial x_3}=0 \qquad (6)$$

where u_i are the velocity vector components in the horizontal Cartesian x_i directions (*i* = 1; 2), u_j are the velocity vector components in the three Cartesian directions x_j (*j* = 1-3), p_{atm} is the atmospheric pressure and v is the turbulent viscosity. ρ is the specific mass, ρ' is its anomaly, ρ_0 is the reference specific mass, η is the free surface level, ρ (η) represents the specific mass at the free surface, *g* is the acceleration of gravity, *t* is the time, Ω is the Earth's velocity of rotation and ε is the alternate tensor. Integrating Eq. (6) over the whole water column (between the free surface elevation η (x,y) and the bottom –*h*, the free surface equation is obtained:

$$\frac{\partial \eta}{\partial t} = -\frac{\partial}{\partial x_1}\int_{-h}^{\eta} u_1\, dx_3 - \frac{\partial}{\partial x_2}\int_{-h}^{\eta} u_2 dx_3 \quad (7)$$

where *h* is the depth.

The bottom shear stress, $\vec{\tau}$, is represented as a quadratic function of velocity (Eq. (8)) and the drag coefficient (C_D) can be parameterized in terms of Manning's friction coefficient (*n*), by applying Eq. (9):

$$\vec{\tau} = C_D\overrightarrow{|V|}V \quad (8)$$

$$C_D = gn^2H^{1/3} \quad (9)$$

where $\vec{V}$ is the horizontal velocity vector and *H* ($H = h + \eta$) is the total depth of the water column. The model discretization is fully described in Martins *et al*. (2001).

2.2.2. Model simulations

Some points in the model simulations were similar for Tagus estuary and Ria de Aveiro lagoon. The wind forcing was not considered once is essentially important in short periods of time in the two systems. Therefore, the main forcing were the tide and river discharges.

Simulations were performed for 32 days (May 2nd to June 3th 2011) but a second period of 14 days, 18 hours, 32 minutes and 24 seconds was also simulated (in order to calculate the residual circulation). The spin-up time was 2 days.

For SLR simulations, the model parameters were kept except the value of the tide elevation. Instead of 2.08 m (considered for the actual scenario simulations) was considered a sea level rise of 0.42 m, that is, the initial elevation value considered for SLR simulations was 2.50 m. The sea level rise value of 0.42 m was adopted because it is a predictable value for the sea level rise in Portuguese coast (Lopes *et al*., 2011a).

Moreover, with the purpose of evaluate the effects of the rivers in the residual circulation patterns, four discharges scenarios were simulated: *Maximum*, *Minimum*, *Typical* and *No Discharges*, both for actual as for SLR situation

2.2.2.1. Tagus estuary simulations

For Tagus estuary, the numerical model was validated by Vaz *et al.,* (2011), comparing harmonic analysis results of measured and model predicted sea surface height for 12 stations covering the whole estuary. The data used in this process was measured in 1972, covering the entire estuary. The model results for sea level height reveal small differences with observations, lower than 5% of the local variation, both in amplitude and phase, in almost stations. Therefore an accurate validation of the tidal propagation was achieved. Hence, the author concluded that the implementation of this model was successful and its application is able to contribute to increase the knowledge of the estuary processes. Consequently, the methodology regarding the simulations for Tagus estuary through the application of Mohid was performed based in this study (Vaz *et al.,* 2011).

In the present work, the numerical model (2D barotropic) includes a three level nesting model (Vaz *et al.,* 2011). The first domain (D1) is a tidal driven model that uses the FES2004 global solution as forcing and has variable horizontal resolution (0.06º). This model domain covers most of the Atlantic coast of Iberia and Morocco. The second domain (D2) has 0.0100º horizontal resolution and is similar to D1. The third domain (D3) has 0.002-0.004º horizontal resolution and includes the Tagus Promontory area and it is directly coupled to D2 at the open boundaries (Vaz *et al.,* 2011). The numerical grid of the third domain presents 335 x 212 cells of 200 m each (Fig.2). On the open ocean boundary of D3, the model input was the tidal forcing from D2 (Vaz *et al.*, 2011) and rivers inflow were imposed in the landward boundaries considering the values of the Table 1 (Neves, 2010).

The time step of the model was 15 s and a horizontal viscosity of 5 $m^2 s^{-1}$ and a rugosity of 0.0025 were considered.

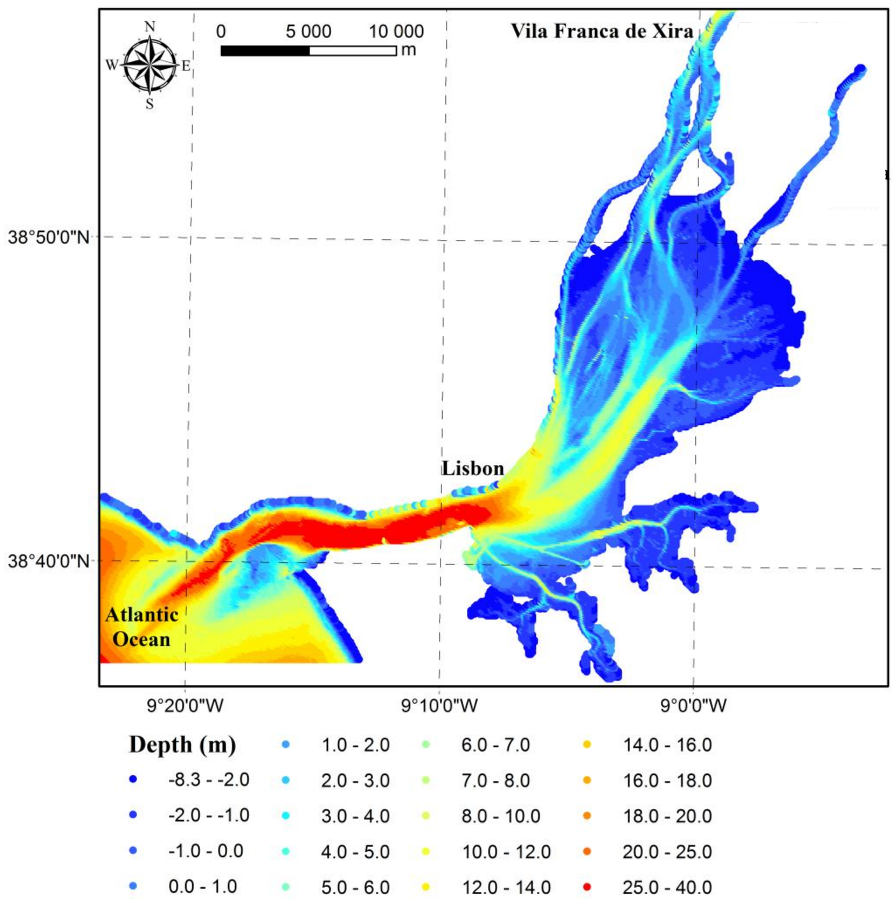

Figure 2: Numerical bathymetry considered in the model simulations for Tagus estuary.

Table 1: River discharges values considered for Tagus estuary simulations.

Discharges (m^3s^{-1})	Tagus	Sorraia	Trancão
Maximum	2000	200	20
Typical	400	40	5
Minimum	40	4	1

2.2.2.2. Ria de Aveiro lagoon simulations

Regarding to Ria de Aveiro lagoon, the model was calibrated and validated by Vaz *et al.* (2007). For the calibration process, the authors used as a first approach a qualitative comparison of the temporal evolution of sea surface elevation (SSE) data measured in 1987/1988 at 9 stations. In general, the disagreement between the computed and observed SEE was low with values lower than 5% of the local tidal range. Therefore, after obtained a good match for all the stations the model's accuracy was evaluated through the determination of the root mean square (RMS) error and also through the comparison between amplitude and phase of the main tidal constituents determined from harmonic analysis of the observed and computed data. The validation procedure was performed using two independent data sets, which includes observations of current velocities at 10 stations and SSE values (1997 data) at 11 stations and measured water fluxes at the lagoon's inlet for the period of October 2002. According to the results obtained in this study performed by Vaz *et al.* (2007), Mohid-2D was successfully implemented, revealing an accurate reproduction of the tidal propagation within Ria de Aveiro. Consequently, the authors concluded that model could be used in future studies concerning the lagoon's hydrodynamics. Therefore, in the present work, the methodology regarding the simulations for Ria de Aveiro lagoon through the application of Mohid was performed based in the study by Vaz *et al.* (2007).

The time step of the model was 6 s and a horizontal viscosity of 20 $m^2 s^{-1}$ was considered. In the calibration and implementation processes, the best adjustment between model results and field observations was achieved through bottom roughness parameterized from Manning's coefficients ranging between 0.022 and 0.045. Consequently, a varying Manning's coefficient was considered.

Ria de Aveiro grid has 429 x 568 cells, with dimensions of 40 x 40 m in the central area of the lagoon and 40 x 100 m in the north and south areas (Fig.3). At the sea open boundary, water elevation over the reference level was imposed using tidal harmonic constituents determined using T_TIDE package (Pawlowicz *et al.*, 2002) and rivers inflow were imposed in the landward boundaries considering the values of the Table 2.

River discharges values were obtained from the *Ria de Aveiro Polis Litoral* program, which considered the data present in the *Plano de Bacia Hidrográfica* (www.arhcentro.pt). In *Ria de Aveiro Polis Litoral,* the mensal average discharges for the main rivers were defined, in average and dried year. Therefore, in the present study, the mean values of the rivers discharges were calculated averaging the series values for each river, which corresponds to the "*Typical"* numbers on the Table 2. After that, the higher discharge value of each river series were considered as the "*Maximum*" value. For the *"Minimum"* values, it was considered reasonable that 20% of the average values were a good representation of the minimums values rivers discharges.

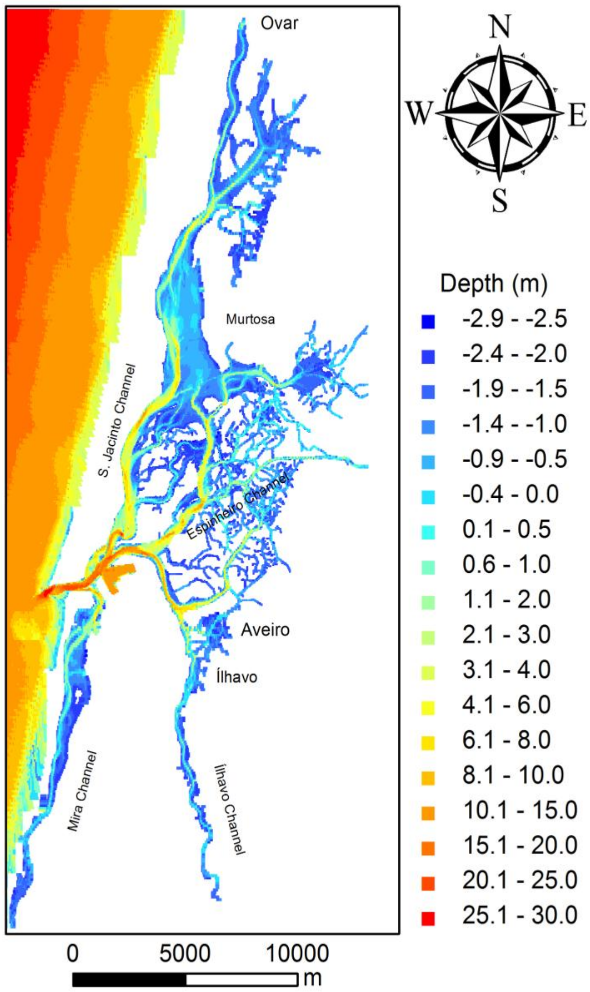

Figure 3: Numerical bathymetry considered in the model simulations for Ria de Aveiro lagoon.

Table 2: River discharges values considered for Ria de Aveiro lagoon simulations.

Discharges (m^3s^{-1})	Vouga	Antuã	Boco	Caster	Rª dos Moinhos
Maximum	517.0	39.0	8.6	13.8	25.6
Typical	60.0	4.5	1.0	1.6	3.0
Minimum	12.0	0.8	0.2	0.3	0.5

2.3. Hydrodynamic parameters

Once one of the main goals of the present work was to study the SLR effects in the local hydrodynamic parameters, two scenarios related with sea level value were evaluated in the numerical simulations: the first one, considering an initial mean level of 2.08 m and, the second one, considering the mean level as 2.50 m, with the respective rise of 0.42 m. For the residual circulation calculations, for each scenario, different situations of river discharges, for both systems, were considered in order to determine the role of the freshwater in this parameter. Moreover, the values of the residual circulation were obtained directly by the model results defining a simulation period of 14 days, 18 hours, 32 minutes and 24 seconds, once this is a multiple period of the tidal constituents M_2 and S_2. With this procedure, the main tidal constituents are filtered, including the fortnight constituents related with the spring and neap tide cycle. For a clear understanding of this methodology, the Figure 4 illustrates the conditions and scenarios considered.

To determine the tidal asymmetry, a simulation period of 32 days was considered and the simulations were performed considering the *Typical* freshwater inflows, once this typical inflow was admitted as the mean values of the rivers discharges in the estuaries. For the tidal dissipation calculations, only a period of 12 hours was necessary to considered and consequently, series of 12 h were evaluated. For a better understanding of these steps, Figure 5 demonstrates the conditions and scenarios considered in this case. A more specific explanation of how these parameters were determinate is also hereafter explained.

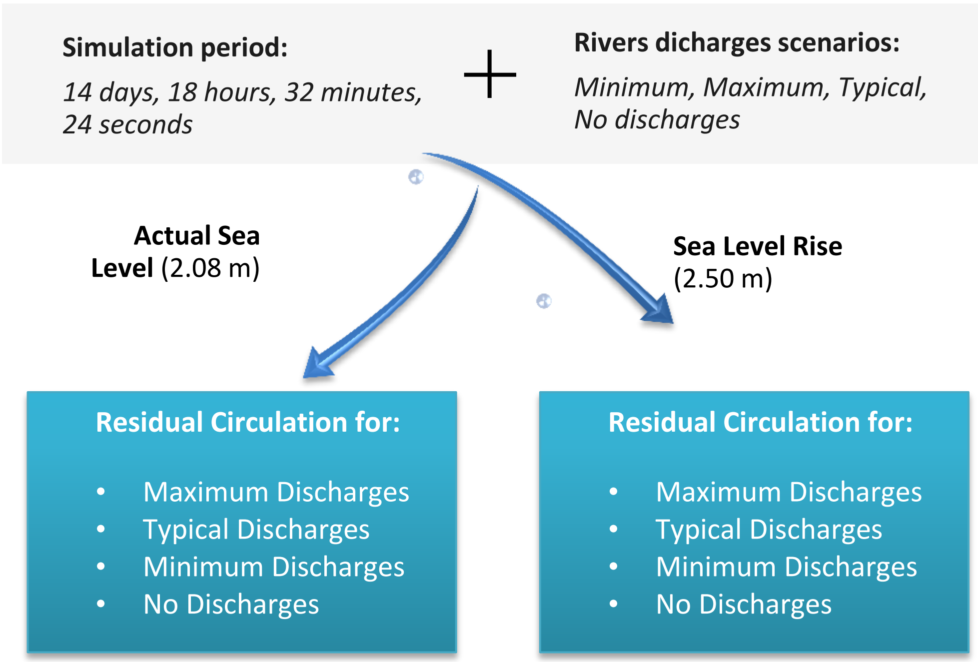

Figure 4: Scheme of the methodology followed to obtain the results for residual circulation under the different conditions and scenarios considered.

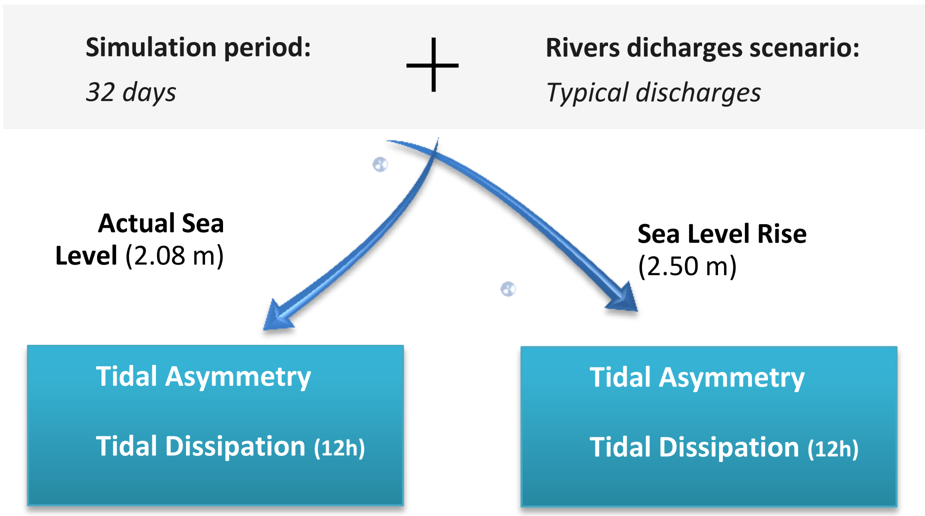

Figure 5: Scheme of the methodology followed to obtain the results for tidal asymmetry and tidal dissipation under the different scenarios considered.

In many coastal worldwide areas where the tide is semi-diurnal, as in the Ria de Aveiro lagoon and Tagus estuary, the dominant tidal constituent is M_2 and thus the shallow water most significant constituent is the M_4, the first harmonic of M_2. M_4 is generated due to the effects of the depth and geometry local alterations in shallow water systems on advective terms, which can change the local tide harmonic effects. Tidal distortion (asymmetry) can be represented by harmonics of astronomical tidal constituents (Aubrey and Speer, 1985). Thus, the ratio of M_4 and M_2 amplitude (which corresponds to the value of A_r) can be analyzed to determinate the magnitude of the tidal asymmetry generated within the Tagus estuary and Ria de Aveiro lagoon. Similarly, the relative phase of M_2 and M_4 determines the type of asymmetry. Therefore, the asymmetrical coefficients A_r (amplitude ratio) and φ (relative phase) can be represented by the following equations (Dias and Sousa, 2009):

$$A_r = \frac{A_{M_4}}{A_{M_2}} \qquad (10)$$

$$\varphi = 2\theta_{M_2} - 2\theta_{M_4} \qquad (11)$$

where A_r is the amplitude, θ indicates the phase and M_4 and M_2 correspond to the tidal constituents. According Dias and Sousa (2009), the flow is flood dominant if 0°< φ<180° and ebb dominant if 180°<φ<360°.

Regarding to tidal dissipation, in this study, the mean rate of dissipation of energy per unit area due to the bottom friction was estimated from the application of the following equation (Burling *et al.*, 2003):

$$\varepsilon = \frac{1}{T}\int_0^T C\rho(U^2 + V^2)^{\frac{3}{2}}\, dt \qquad (12)$$

where U and V are the x and y components of the current, respectively and C represents the Chézy coefficient determined from de Manning friction coefficient n. The integration presented in the equation (12) was taken over one tidal cycle for neap and spring tide cases.

Horizontal fields for residual circulation, tidal asymmetry and dissipation were performed for all the scenarios and situations simulated and are present in the next chapter. Moreover, absolute and percentage differences between the results for actual and SLR situations were calculated in order to achieve a better interpretation of the SLR effects in the patterns of the hydrodynamic parameters.

3. Results and Discussion

3.1. Residual circulation

Residual circulation analysis is important because it determines the long-term transport in estuaries and lagoons and, therefore, is a key parameter in the dynamical behavior of these coastal systems. These currents are typically one or two orders of magnitude lower than the instantaneous currents, and are generated through the interaction of the tidal currents with topographic features (Pugh, 1987).

In this work, four distinct scenarios of freshwater inputs were considered (*Maximum*, *Typical*, *Minimum* and *No Discharges*) in order to evaluate the importance of the freshwater in this hydrodynamic parameter. The scenario with *No Discharge* allows the understanding of the tidal forcing in the systems residual circulation patterns and, thus, a quickly perception of the rivers influence. For SLR results, the situation of *Minimum Discharges* was not considered once is very similar with the scenario of *Typical Discharges*.

3.1.1. Residual circulation in Tagus estuary

3.1.1.1. The effect of rivers discharges

The model results reveal that, generally, residual circulation is two orders of magnitude lower than the tidal current, as was expected.

Figure 6 presents the residual circulation results for the four scenarios of river discharges. For a better interpretation, in this case, the difference between *Typical Discharges* and each one of the others scenarios were also calculated and present both in absolute value as in percentage (Fig.7). These calculations allow a quickly perception of the effect of each river discharge scenario in the overall pattern of residual circulation.

The observation of the results presented in the Figure 6 reveals that residual current direction is outwards the system, as it is possible to confirm by the currents direction representing by the arrows.

In the four scenarios under analysis, the area where residual circulation is higher is the upper estuary, probably due to the proximity of the main rivers inflow (Fig.6). In a significant part of Tagus estuary, residual circulation is not higher than 5 cm/s (blue areas) but can rise to more than 20 cm/s in the main channels of the upper bay as in the system mouth (red colours). Face to *Typical* inflow, in *Maximum* scenarios, residual circulation value increases from about 7 to more than 10 cm/s in the deepest channels of the upstream part of the upper estuary and, in the zone closest to the river (Vila Franca de Xira), the values rise from about 14 to more than 30 cm/s. In *Maximum Discharges* scenario, the influence of topography and system morphology is notorious by the presence of strongest currents in the deepest channels of the system. With higher rivers inflow, residual circulation rises significantly, being stronger than in other scenarios, demonstrating the importance of the freshwater inflow in this hydrodynamic parameter.

Considering average values, in the main channel, residual circulation is approximately 3.5 cm/s, 6.1 cm/s, 3.1 cm/s and 2.9 cm/s in *Typical*, *Maximal*, *Minimum* and *No Discharges* scenarios, respectively. In the deeper channels of middle bay, values reach 4.1 cm/s, 7.0 cm/s 2.6 cm/s and 2.5 cm/s and in the channel close to the river mouth, reach 9.5 cm/s, 23.9 cm/s, 7.9 cm/s and 7.6 cm/s in *Typical*, *Maximal*, *Minimum* and *No Discharges* scenarios, respectively (Fig.6).

From the analysis of the absolute differences (Fig.7), the higher differences between the scenarios are more important in the upper bay, as expected, due to the freshwater inputs in that area. While the differences between *Typical* and *Maximum Discharges* could be more than 10 cm/s, in *Typical* and *Minimum Discharges*, the difference are not higher than 2 cm/s for the majority estuary.

The comparison between *Typical* and *No Discharges* scenarios (Fig.7), considering the percentage differences, shows that river effect could rise residual current intensity more than 30%, namely in the upper estuary (from 2cm/s to more than 6 cm/s higher in the lower and upper bay, respectively, in *Typical Discharges*) which, once again, reveal the strength of Tagus river. *Typical* and *Minimum Discharges* maximal differences could be higher than 30% particularly near the rivers discharges, with *Typical Discharges* situation presenting the higher values.

Model results indicate that rivers discharges effect cannot be unconsidered once residual currents intensity could be 40% higher in *Typical* inflow than in *No Discharges* scenario. As such, Tagus river can influence significantly the residual circulation patterns and in *Maximum Discharges*, residual current intensity could be more than 100% higher than in *Typical* inflow situation.

Regarding to Rosário salt marsh, Figure 8 demonstrates that the direction of the flow remains similar in the four situations. Generally, residual circulation is less than 2 cm/s in the salt marsh area. In *Typical* and *Maximal Discharges* is about 1.29 cm/s, 1.23 in *Minimal Discharges* and 1.35 cm/s in *No Discharge* situation. These results mean that, in the salt marsh area, residual circulation is 5% less in *Minimum Discharges* than in *Typical Discharges* (Fig.9). *No Discharges* situation means an increase of about 5% relatively to *Typical* freshwater inflow (Fig.9). The residual circulation results reveal that the freshwater inflow is not significant in the Rosário salt marsh possible because Rosário is located in a secondary channel, in a shelter area.

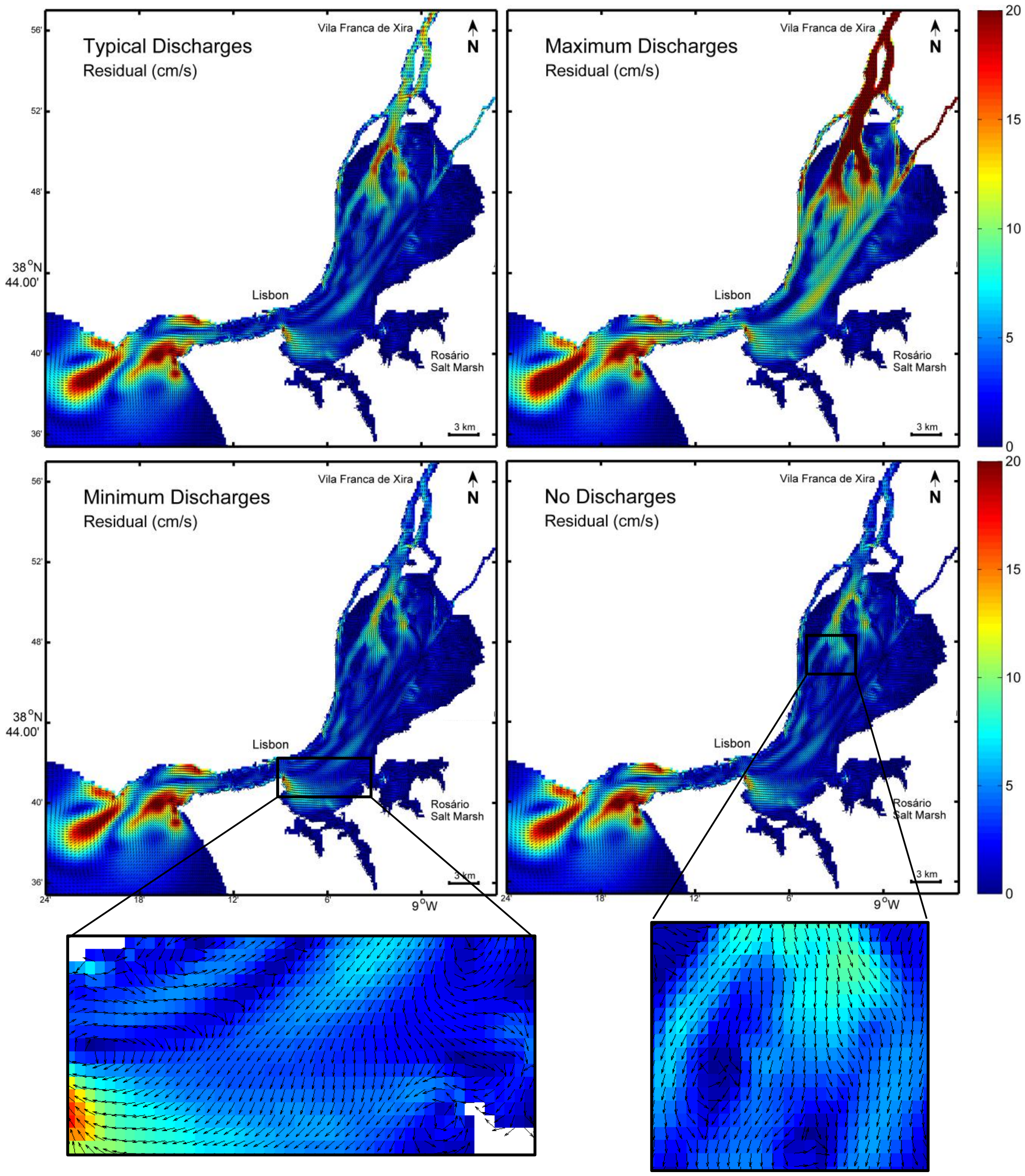

Figure 6: Residual circulation (cm/s) in Tagus estuary for the different study cases: typical discharges (upper, left), maximum discharges (upper, right), no discharges (base, right) and minimum discharges (base, left). The amplified figures allow a better observation of the current direction.

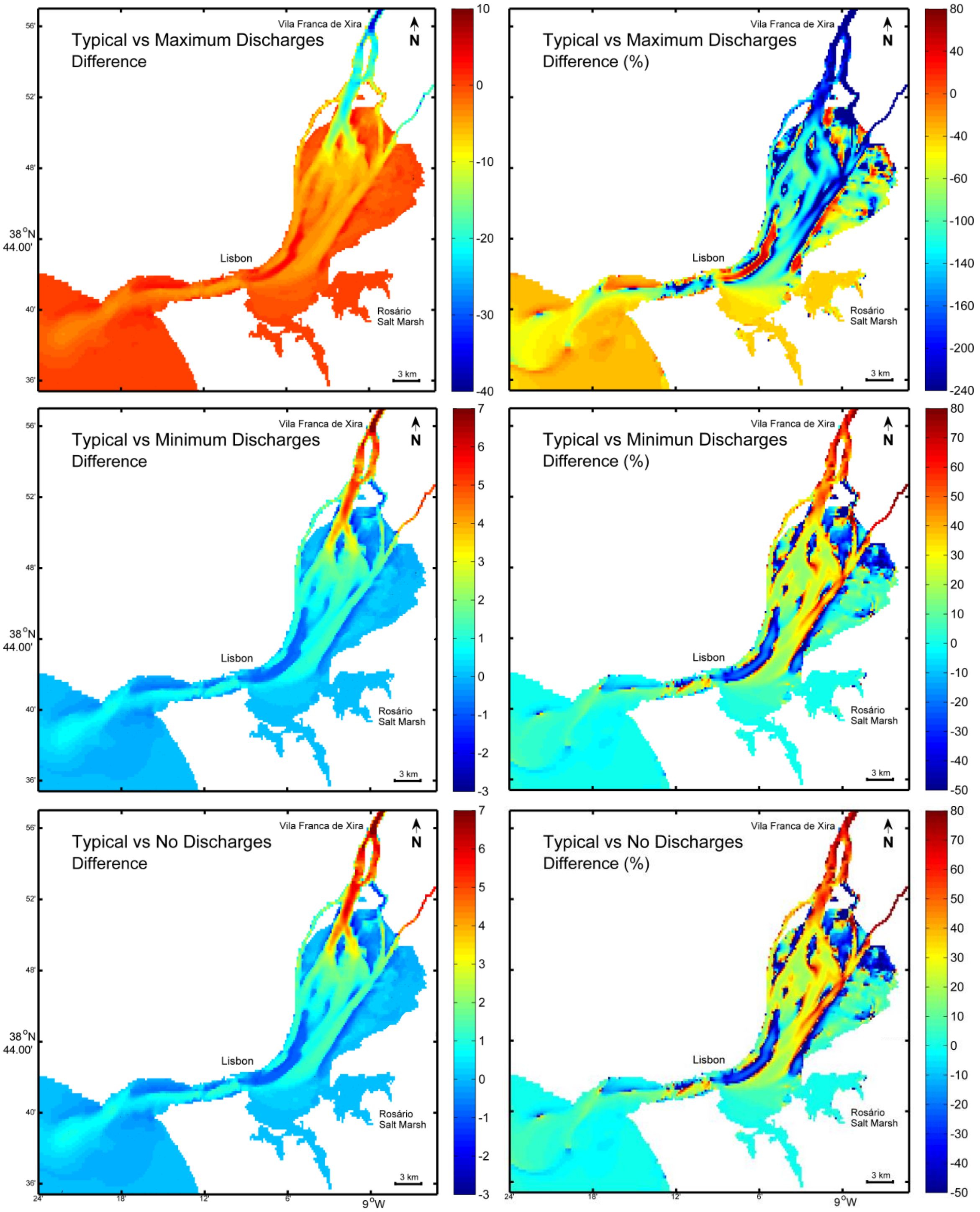

Figure 7: Absolute (left) and percentage (right) difference of residual circulation intensity between typical discharges and the different studied scenarios for Tagus estuary discharges; from upper to the base are represented the comparison between typical and maximum, minimum and no discharge scenarios, respectively.

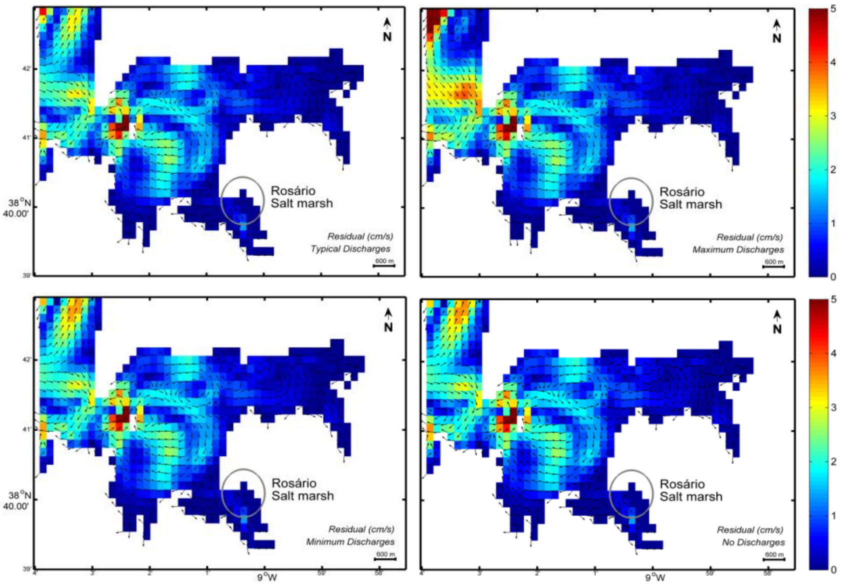

Figure 8: Residual circulation (cm/s) in the especific Tagus estuary salt marsh study area (Rosário). From letf to rigth are represented typical and maximum discharges (upper) and minimum and no discharges scenarios (lower).

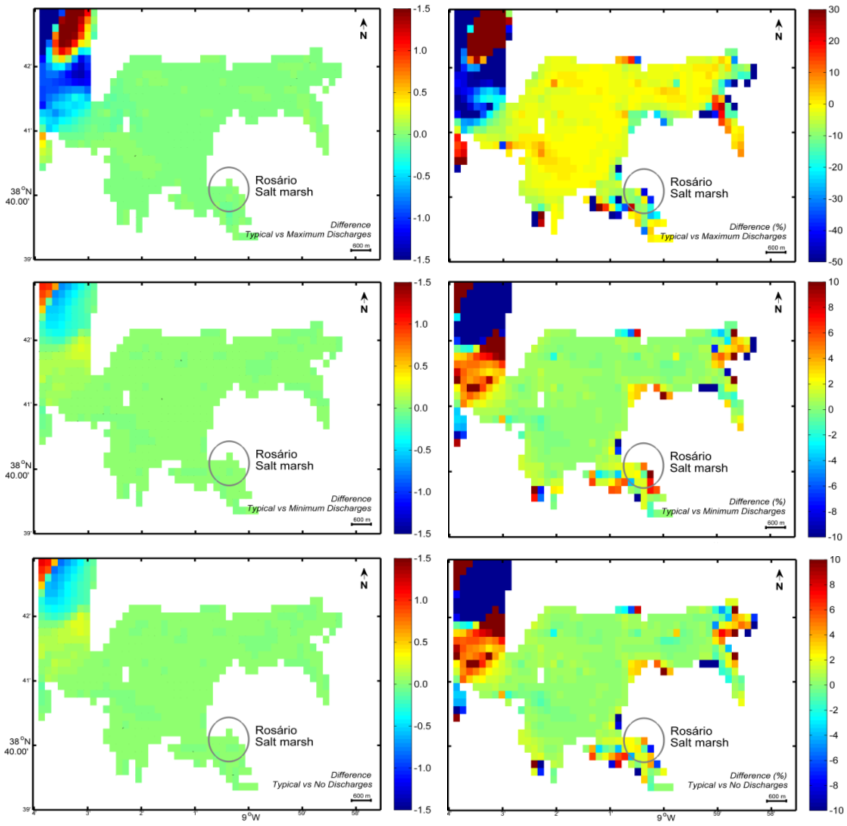

Figure 9: Absolute (left) and percentage (right) difference of residual circulation intensity between typical discharges and the different studied scenarios for Rosário salt marsh (Tagus estuary); from upper to the base are represented the comparison between typical and maximum, minimum and no discharge scenarios, respectively.

3.1.1.2. Sea level rise effects in residual circulation

Generally, sea level rise results for residual circulation in Tagus estuary (Fig.10) reveal that the patterns of this parameter in the system remain similar to those found in the actual sea level scenario.

A first observation of the absolute difference (Fig.11) reveals that residual circulation increase about 1 cm/s in some areas of the system mouth and in some shallow areas of the bay (blue areas), while in the deepest channels of the bay residual circulation decrease 1 or even more than 3 cm/s in SLR scenario.

In *Typical Discharges*, SLR scenarios show residual circulation values between 10 and 30% lower for actual scenarios, namely in the upper bay. In *Maximum* scenarios, differences are not so high and SLR results present a maximal decrease of 20%, showing for the majority of the bay area values 9% lower than in actual sea level scenarios. The difference pattern in *Typical* and *No Discharges* scenarios are similar, while in *Maximum Discharges* the differences are more homogeneous.

As concluded before, the salt marsh is not significantly affected by the rivers inflow, therefore the different rivers discharges scenarios are similar for all situations (Fig.12). Thus, in Rosário salt marsh, in *Typical, Maximum and No Discharges* scenarios*,* residual circulation increase in average about 20%, but in some places sea level rise scenario induces values more than 40% higher for than actual scenario. Therefore, with SLR, considering average values, residual circulation rise from about 1.30 cm/s to about 1.60 cm/s.

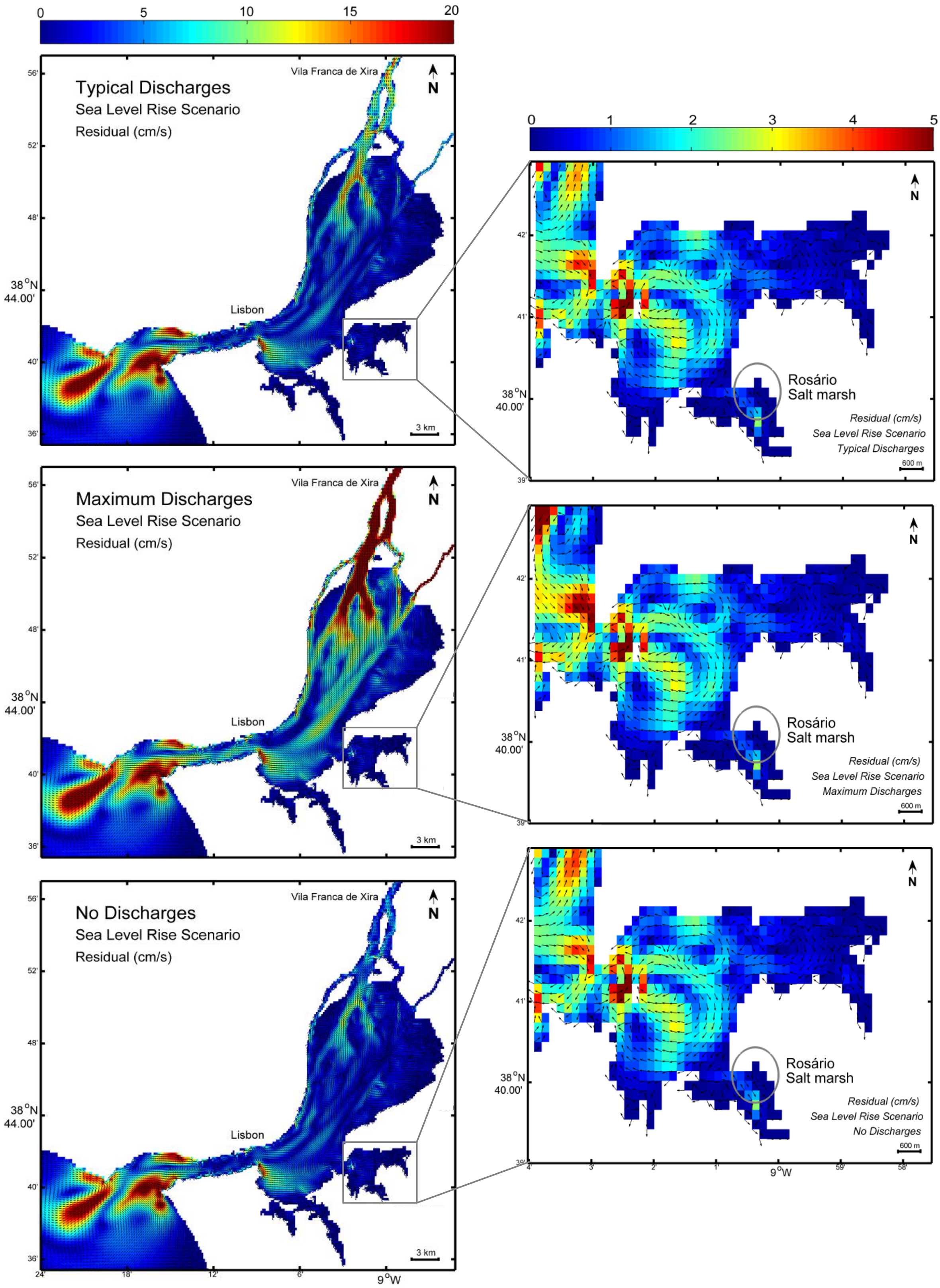

Figure 10: Residual circulation values (cm/s) for sea level rise scenario for Tagus estuary. From upper to base are represented typical, maximum and no discharges situations, respectively. In the right side are presented an amplification of the results for Rosário salt marsh.

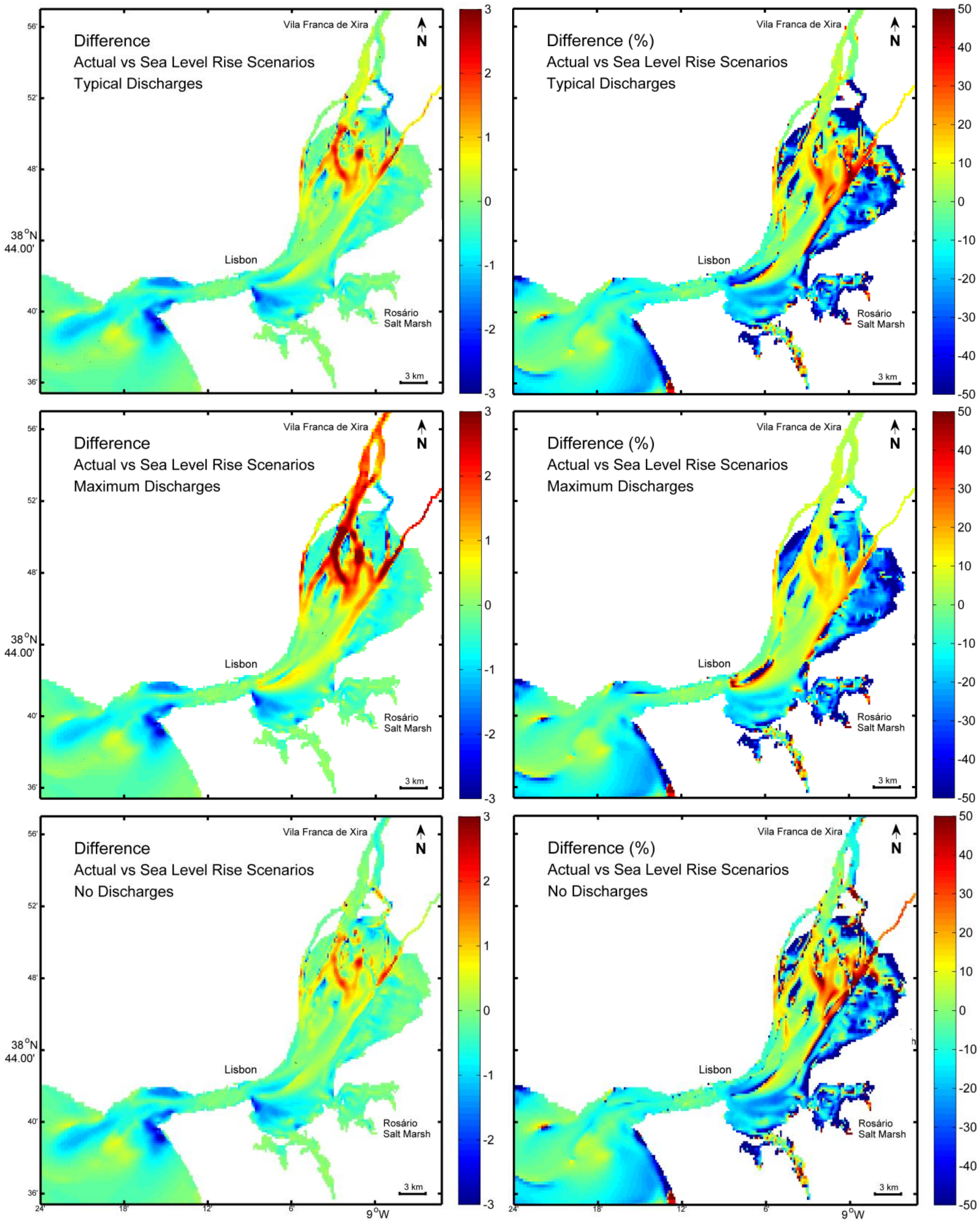

Figure 11: Absolute (left) and percentage (right) difference of residual circulation values between actual and sea level rise scenarios for the different discharges situations in Tagus estuary; from upper to the base are represented typical, maximum and no discharge scenarios, respectively.

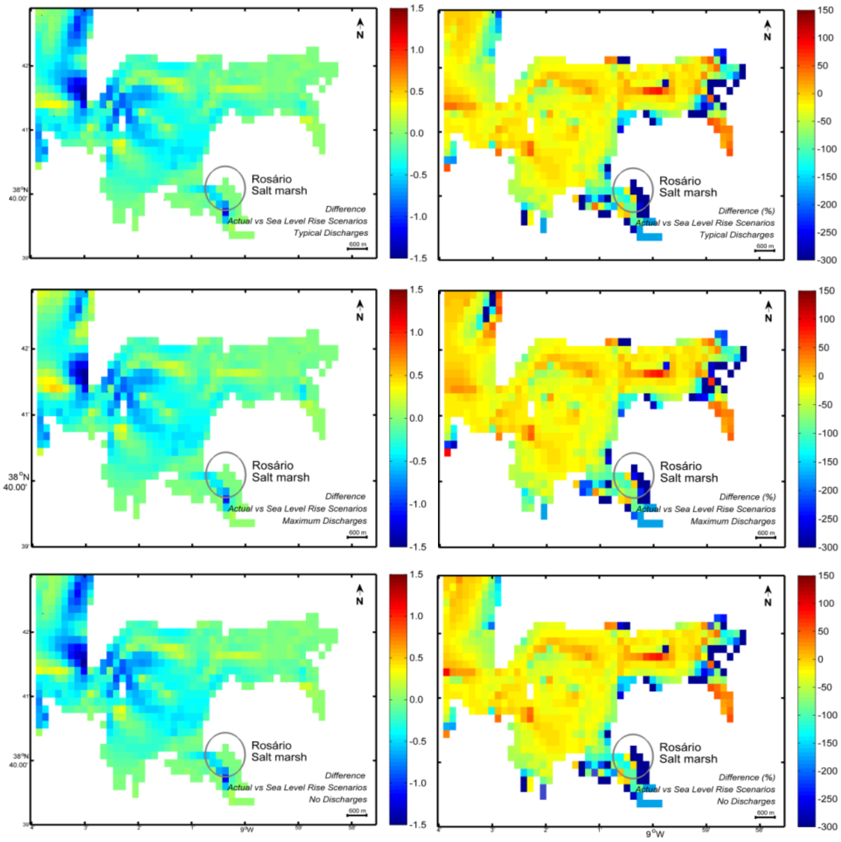

Figure 12: Absolute (left) and percentage (right) difference of residual circulation intensity between actual and sea level rise scenarios for the different discharges situations in Rosário salt marsh (Tagus estuary); from upper to the base are represented typical, maximum and no discharge scenarios,

3.1.2. Residual circulation in Ria de Aveiro lagoon

3.1.2.1. The effect of rivers discharges

Figures 13 and 15 present the residual circulation model results for the four scenarios of river discharges in the case of Ria de Aveiro lagoon and for the Barra salt marsh, respectively. As performed for Tagus estuary, for a better interpretation, the difference between *Typical Discharges* and each one of the others scenarios was calculated and is presented both in absolute value as in percentage (Figs. 14, 16).

Vouga and Antuã rivers are the main freshwater sources of Ria de Aveiro, although the effects of the other freshwater should also be considered. Considering the mean values of this rivers inflow, the river discharges influence is moderate in terms of the general circulation of the lagoon, but it is expected a significant influence in the lagoon residual circulation (Lopes and Dias, 2011).

Residual circulation induced by the tide, presented in Figure 13, generally, has two orders of magnitude less than tidal currents, as it was verified by other authors such Lopes and Dias (2011). In this work, it is also observed that residual current is ebb dominated, through the analysis of the current direction (figures amplification presented in Figure 13).

In the central area of the lagoon, in *Typical* flows condition (Fig.13), is in the S. Jacinto channel that residual circulation raises its higher intensity, reaching 9 cm/s in some places. Mira and Espinheiro channel also shows considerable values of residual circulation, higher than 6 cm/s in certain areas. Close to Vouga river mouth, residual circulation could reach 30 cm/s, because of the proximity of the river input. The pattern found in *Mininum Discharges* is similar, but in the Vouga river area values are not so high (an average of 5 cm/s).

In *Maximum Discharges* scenario (Fig.13), residual circulation rises to more than 10 cm/s in the lagoon mouth, Espinheiro and S.Jacinto channels and also in some channels close to Vouga and Antuã rivers mouth. In Espinheiro channel and Vouga river zone, values can be higher than 17 cm/s. Residual circulation in S. Jacinto channel rises to 14 cm/s, but the Espinheiro channel is now where residual current reaches its maximum value, more than 18 cm/s.

Considering the situation of *No Discharges* (Fig.13), in general, is observed that the stronger values of residual circulation decrease in the entire system comparing to the other scenarios.

A first observation of the comparison between the absolute differences scenarios (Fig.14) shows that the main differences occur in the deepest areas of the main channels. The comparison between *Typical* and *No Discharges*, demonstrate the influence of rivers inflow in residual circulation. The *No Discharges* scenario, in general, present values 20% lower in the entire lagoon relatively to *Typical Discharges*. In *Typical* situation, in some places, such as the middle zone of S. Jacinto channel, values can be almost 80% higher than those found in *No Discharge* scenario. Near the rivers sources, the differences are higher because the comparison is between no freshwater incoming with *Typical Discharge* values.

The differences between scenarios are minimal for *Typical* and *Minimum Discharges*, being lower than 10% in a large area which means a difference less than 1 cm/s in almost system.

Results of *Maximum Discharge* scenarios indicate that, under this condition, residual circulation suffers a significance alteration in the Ria de Aveiro. In fact, in Espinheiro channel and in the first half of S.Jacinto channel, residual circulation could be 70% higher than that one found in *Typical Discharges* (could reach 17 cm/s in lagoon’s mouth and in Espinheiro channel, instead of 9 cm/s in *Typical Discharges* scenario, and 14 cm/s instead of 9 cm/s in S.Jacinto channel, for example).

Figure 14 shows that in *Minimum Discharges* residual circulation is lower than 5% of the typical value in practically all system, and a *Maximum Discharges* means an increase of at least 60% of *Typical Discharges* residual circulation in most system.

Figure 15 indicates that in Barra salt marsh the flow direction is similar in the four scenarios. In the salt marsh area, the average value of the residual circulation is close to 3.9 cm/s, 2.9 cm/s, 2.7 cm/s and 2.3 cm/s in *Maximum*, *Typical*, *Minimum* and *No Discharges* scenarios, respectively, which demonstrate the effects of the Ribeira dos Moinhos discharges (Fig.1). These results indicate that residence time increase from *Maximum* to *No Discharges* situations. This situation suggests that in *Minimum Discharges* the renewal of water properties could be lower and salt marsh plants could experience a stress situation. Figure 15 also shows that transport is outward of the salt marsh area. This pattern was also found in Rosário salt marsh.

According to Figure 16, the results suggest that at *Maximum Discharges* scenario the residual circulation is about 35% higher, which means 1 cm/s higher than for *Typical Discharges*. For *Minimum Discharges*, residual circulation is approximately 8% lower, decreasing 0.1 cm/s comparing to the *Typical* flow. Once again, the comparison between *Typica*l and *No Discharges* show the importance of the freshwater in the lagoon: residual circulation decrease almost 20% in the salt marsh in *No Discharges* situation. Comparing to the results found for Rosário salt marsh, Barra salt marsh is visibly more affected by the freshwater inflow.

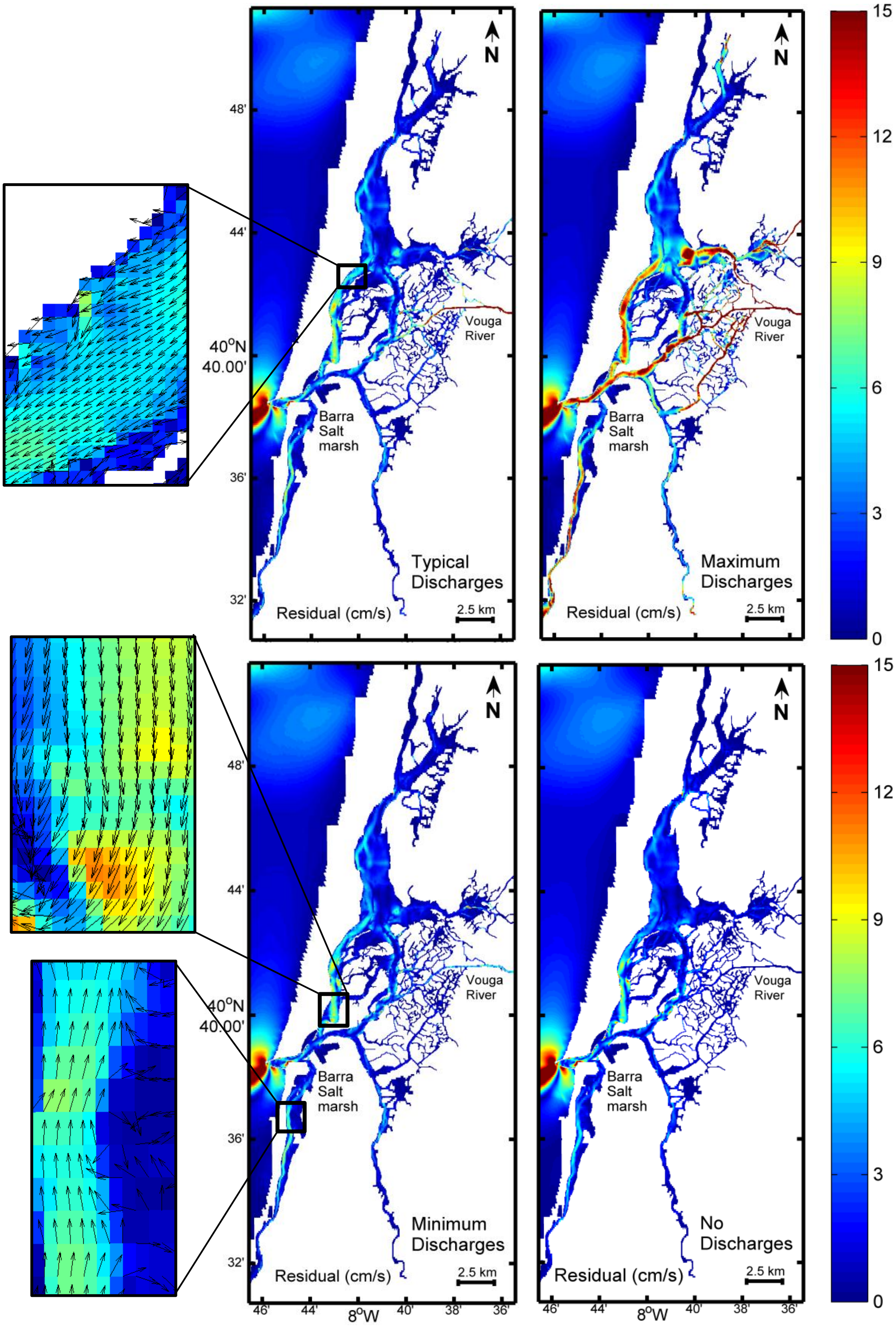

Figure 13: Residual circulation (cm/s) in Ria de Aveiro for the different study cases: typical discharges (upper, left), maximum discharges (upper, right), minimum discharges (base, left) and no discharges (base, right). The amplified figures allow a better observation of the current direction.

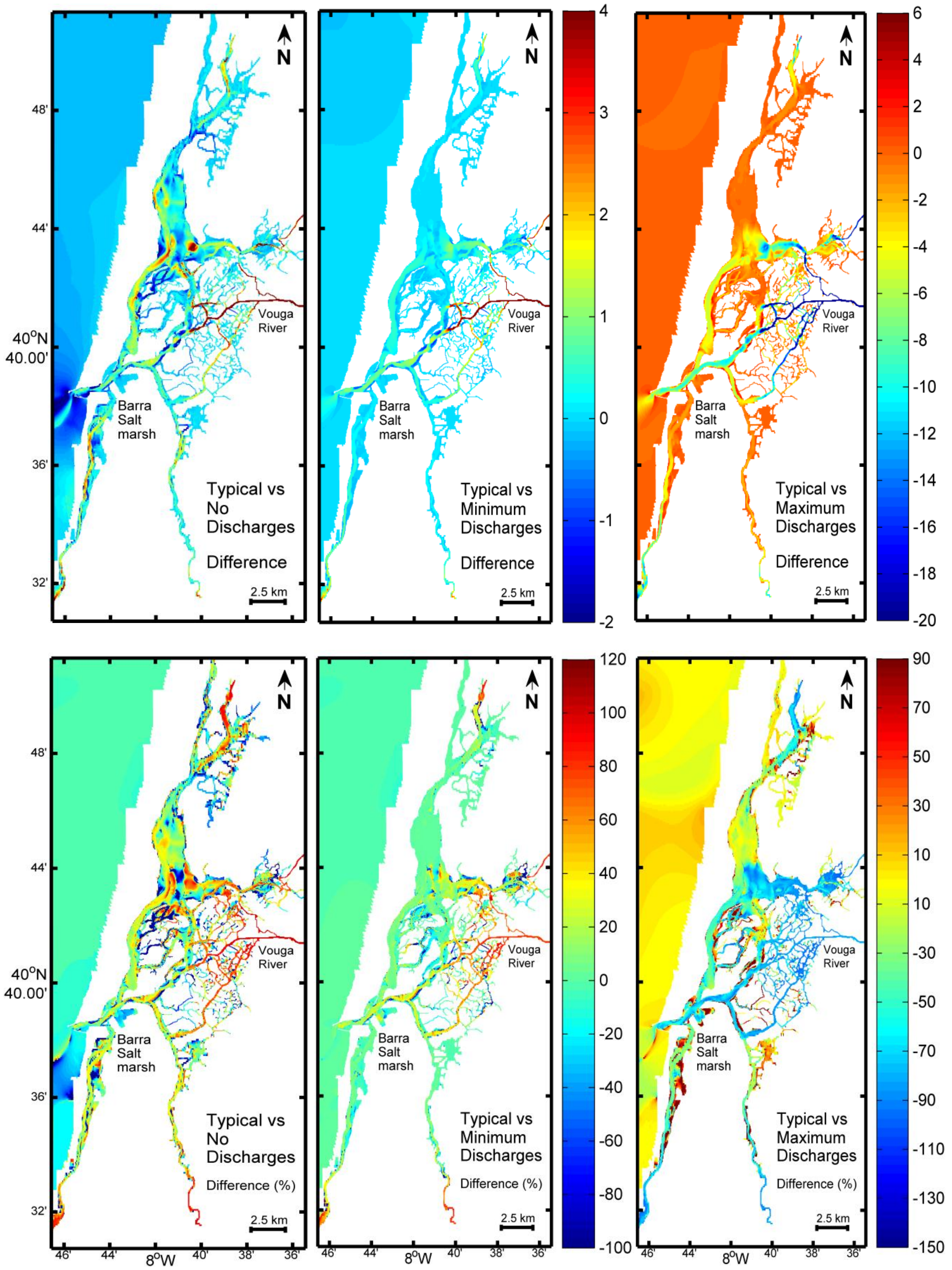

Figure 14: Absolute (upper) and percentage (base) difference of residual circulation intensity between typical discharges and the different studied scenarios for Ria de Aveiro lagoon discharges; from left to the right are represented the comparison between typical and no, minimum and maximum discharge scenarios, respectively.

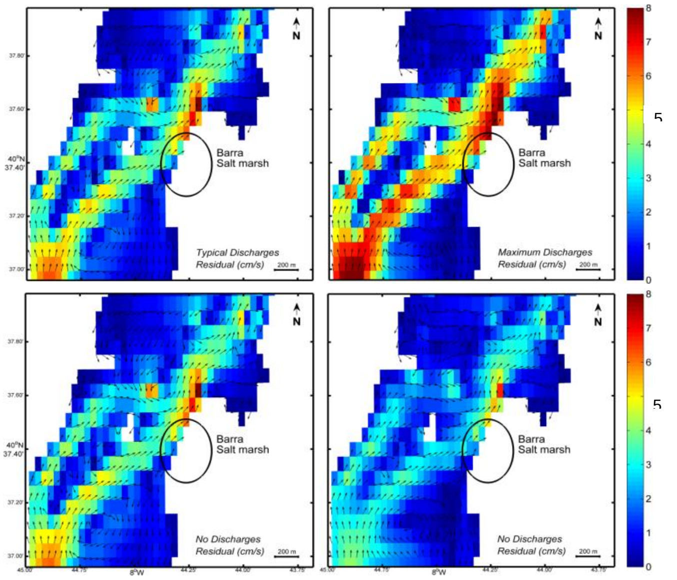

Figure 15: Residual circulation (cm/s) in the especific Ria de Aveiro lagoon salt marsh study area (Barra). From letf to rigth are represented typical and maximum discharges (upper) and minimum and no discharges scenarios (base).

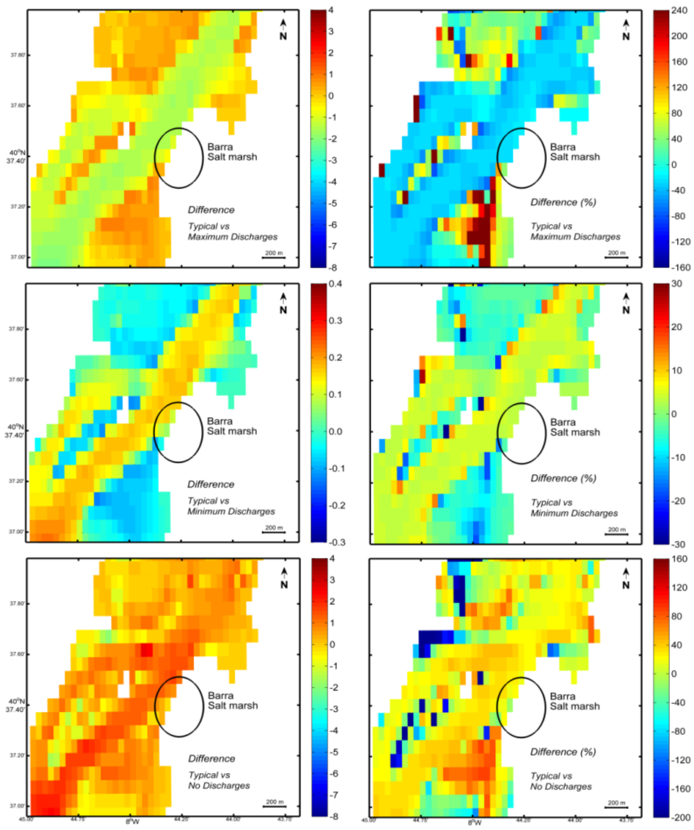

Figure 16: Absolute (left) and percentage (right) difference of residual circulation intensity between typical discharges and the different studied scenarios for Barra salt marsh (Ria de Aveiro); from upper to the base are represented the comparison between typical and maximum, minimum and no discharge scenarios, respectively.

3.1.2.2. Sea level rise effects in residual circulation

The interpretation of Figures 17, 18 and 19 indicates that, in sea level rise scenario, the patterns are similar with that found for the actual scenarios but residual circulation decrease for the entire lagoon. This situation could be explained by the lower bottom friction effect due to the higher water column in SLR scenario.

Generally, with sea level rise, residual circulation decrease approximately 20 %, 15% and 10% in *Typical*, *Maximum* and *No Discharges*, as observed in the yellow areas. The places where residual circulation will increase are the narrow and shallow channels in the complex areas of the lagoon (blue colours) (Fig.16).

More precisely, results indicate that, for example, in S.Jacinto channel, considering the average values, residual circulation will decrease 16 %, 7 % and 5%, that is, decrease 0.9 cm/s, 0.8 cm/s and 0.2 cm/s in *Typical*, *Maximum* and *No Discharges* scenarios, respectively. In Espinheiro channel, residual circulation will decrease 11%, 17% and 1.3%, i.e., decrease about 0.10 cm/s, 2.5 cm/s and 0.03 cm/s in *Typical*, *Maximum* and *No Discharges* scenarios, respectively. Therefore, the less significant differences were found in *No Discharges* scenario proving, once again, the importance of the rivers in determining the residual circulation of the lagoon.

In Barra salt marsh, results indicate that residual circulation will decrease about 11%, 15 % and 2.5%, which corresponds to a decrease of 0.60 cm/s, 0.85 cm/s and 0.07 cm/s in *Typical*, *Maximum* and *No Discharges* scenarios, showing both the importance of the SLR and rivers inflow in this area.

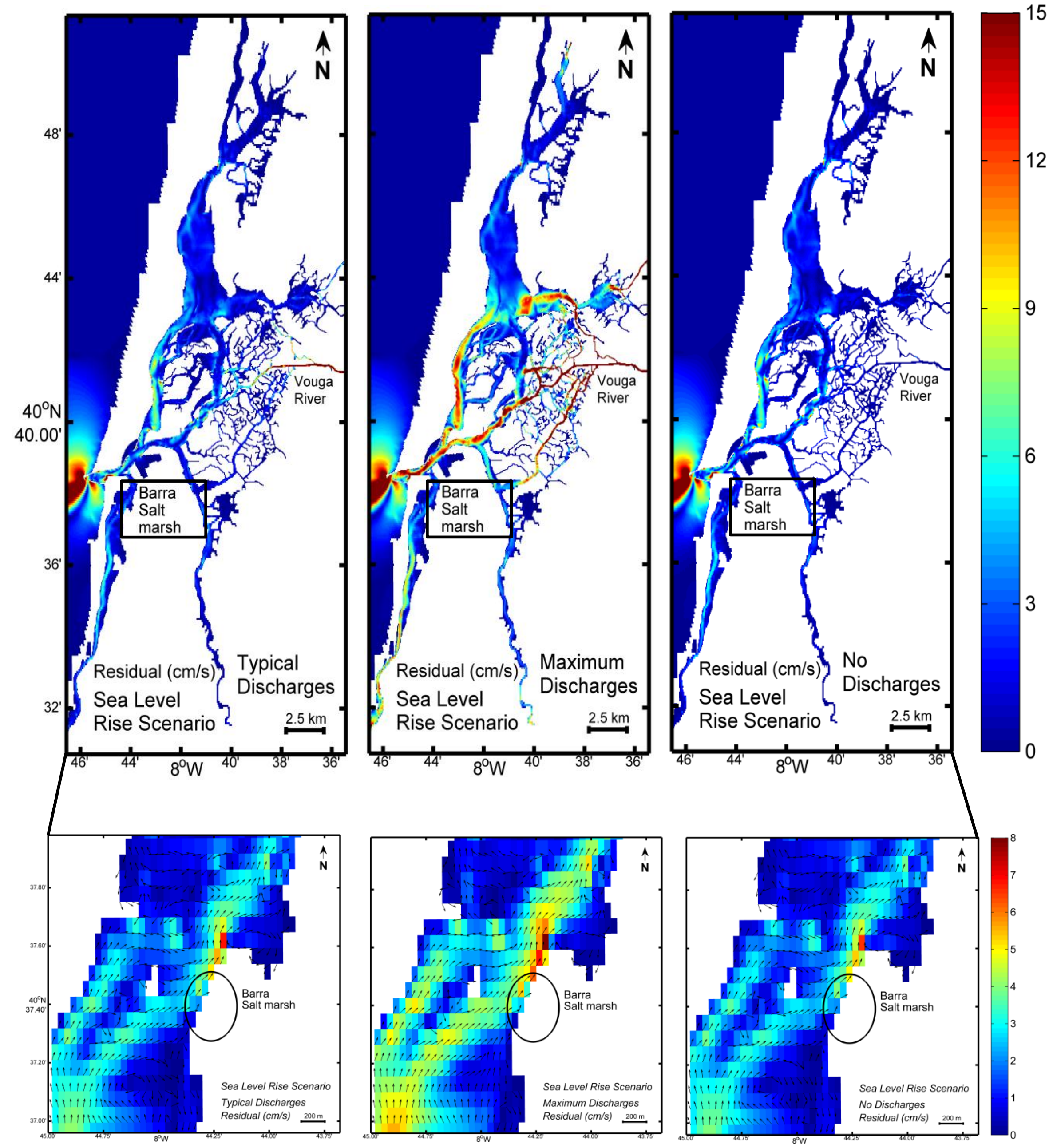

Figure 17: Residual circulation results (cm/s) for sea level rise scenario in Ria de Aveiro lagoon (upper) and Barra salt marsh (base). From left to right are represented typical, maximum and no discharges situations, respectively.

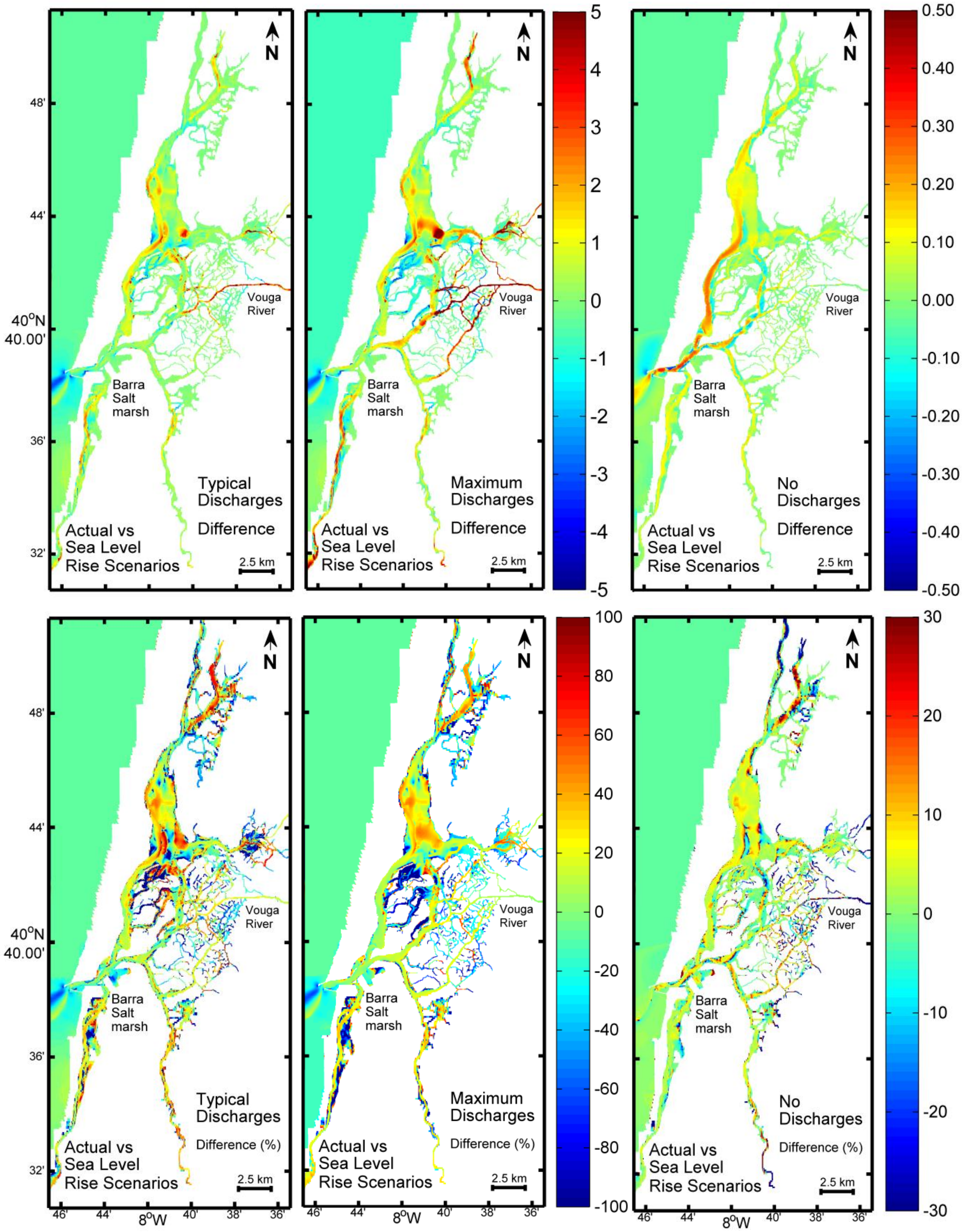

Figure 18: Absolute (upper) and percentage (base) difference of residual circulation values between actual and sea level rise scenarios for the different discharges conditions in Ria de Aveiro lagoon; from left to the right are represented typical, maximum and no discharge scenarios, respectively.

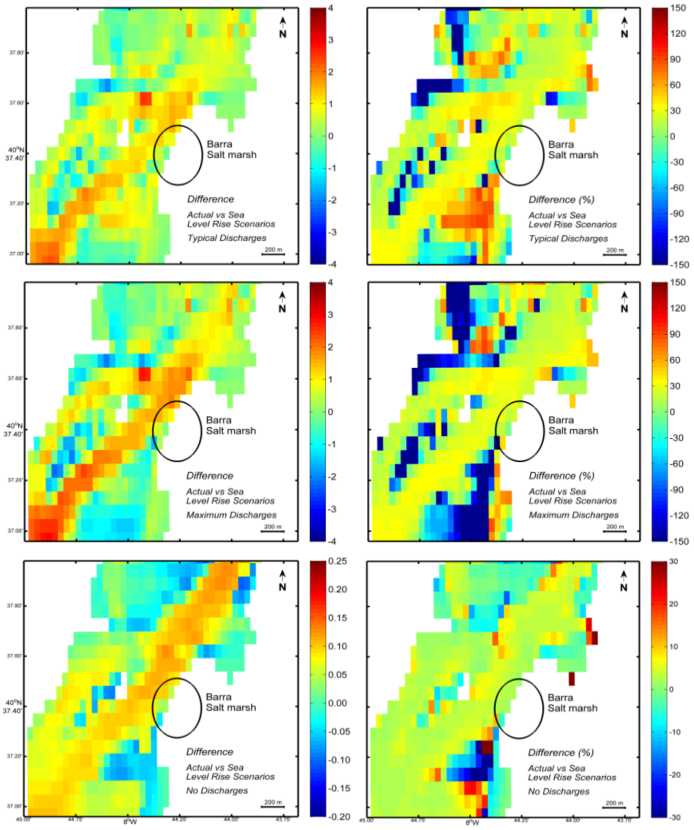

Figure 19: Absolute (left) and percentage (right) difference of residual circulation intensity between actual and sea level rise scenarios for the different discharges situations in Barra salt marsh (Ria de Aveiro lagoon); from upper to the base right are represented typical, maximum and no discharge scenarios, respectively.

3.2. Tidal asymmetry

According to Dias and Sousa (2009), the flood or ebb dominance situations induced by the tidal asymmetry creates net sediment transport over a tidal cycle. Flood-dominated currents results in net sediment transport into the estuary and, in the other side, under ebb dominant conditions, the opposite happens and net seaward transport will take place causing sediment export from the estuary. In fact, tidal asymmetry is frequently the dominant factor determining net sediment transport and deposition, which results in sediment trapping in coastal areas and estuaries (Castaing and Allen, 1981), which is an important factor for salt marsh plants.

3.2.1. Tidal asymmetry in Tagus estuary

Figures 20 and 21 show the amplitude ratio (A_r) and relative phase (φ) for actual and SLR scenarios. The absolute and percentage differences between the two scenarios are also presented in Figure 22.

As referred by Fortunato *et al.* (1997), the amplitude ratio increases within the system and, in this case, this pattern is found for both scenarios. In actual scenario (Fig.20), the amplitude ratio ranges between 0.02 and 0.08, increasing progressively within the estuary, except in the upper bay. With sea level rise (Fig.20), A_r decreases, varying now between 0.02 and 0.06, which demonstrate that shallow water effects become less important possible, to the increase of the water column height induced by the sea level rise. Thus, M_4 amplitude decrease and consequently, amplitude ratio also decreases. Globally, in SLR scenarios the values decrease 12% in main channel and 30% in the bay (Fig.22). In Rosário salt marsh, generally, in SLR scenarios the values decrease almost 20% (Figure 23), being 0.70 in actual scenario and approximately 0.58 (Fig.20) in SLR.

Regarding to relative phase, as expected, Figure 21 indicates that Tagus estuary is ebb dominated once values are higher than 180º in almost system. Once again, this trend is observed in both scenarios. Figure 22 shows that the differences between the two scenarios are not enough to change the ebb dominance. In general, differences are lower than 10º. In Rosário salt marsh, with SLR, the relative phase decreases, possible due to the higher water column that reduces the shallow water effects and, consequently the ebb dominance. These results could indicate that flood durations might increase in salt marsh with SLR, which is a recognizable stress factor to salt marsh plants.

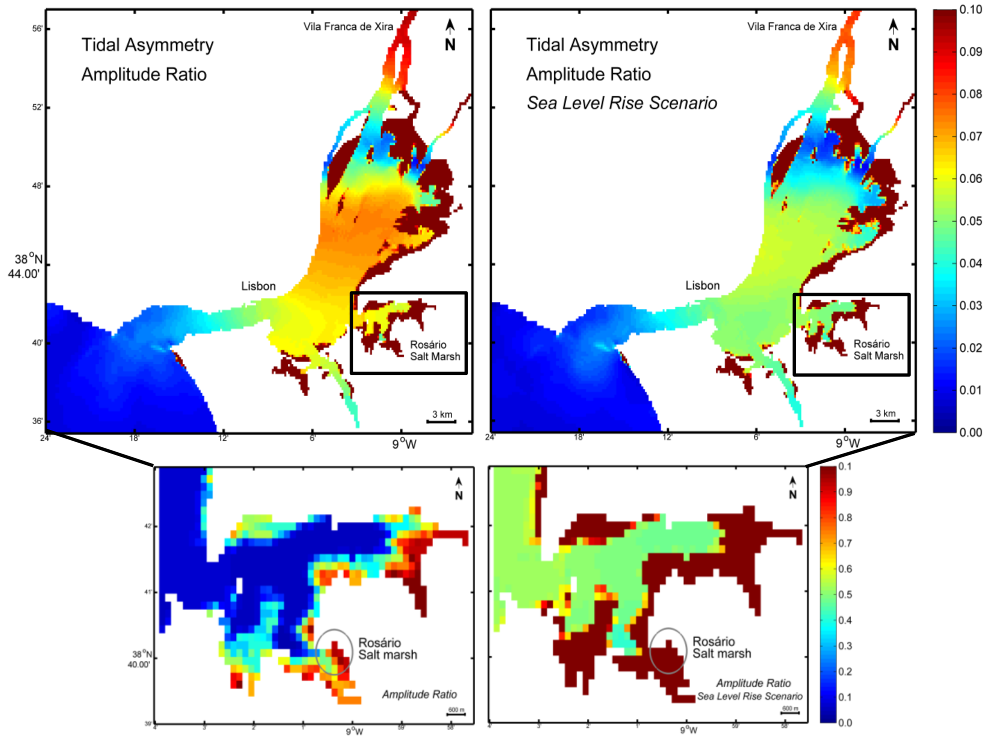

Figure 20: Tidal asymmetry results of amplitude ratio A_r for actual (left) and sea level rise scenarios (right) in Tagus Estuary and in Rosário salt marsh, in detail (base).

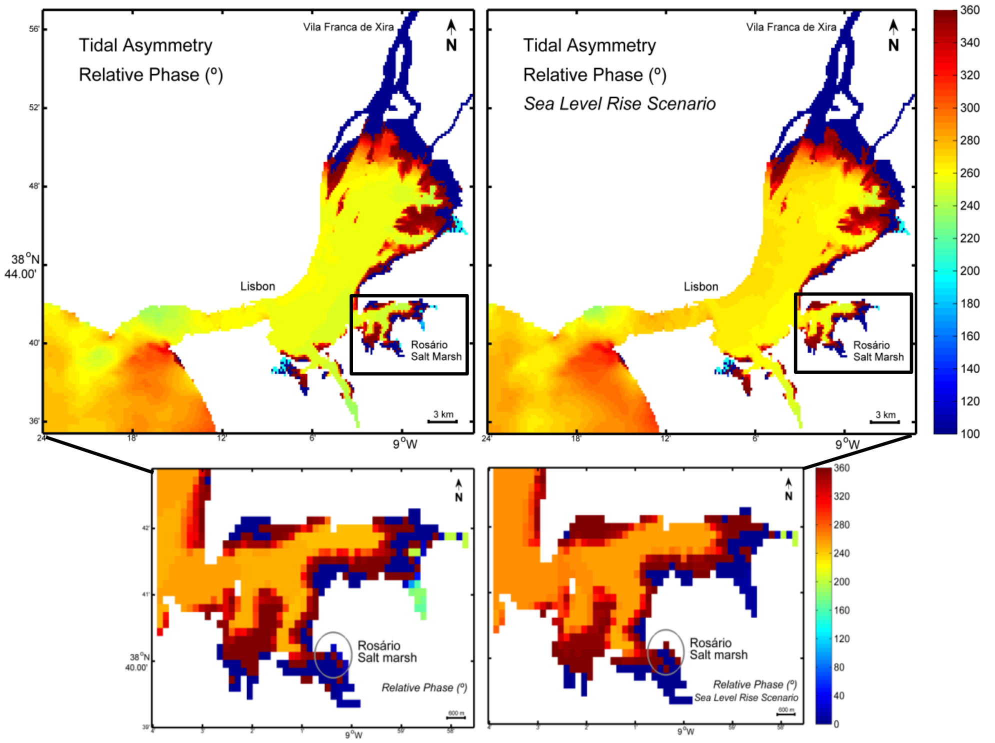

Figure 21: Tidal asymmetry results of relative phase φ (in degrees (°)) in Tagus estuary and in Rosário salt marsh, in detail (base).

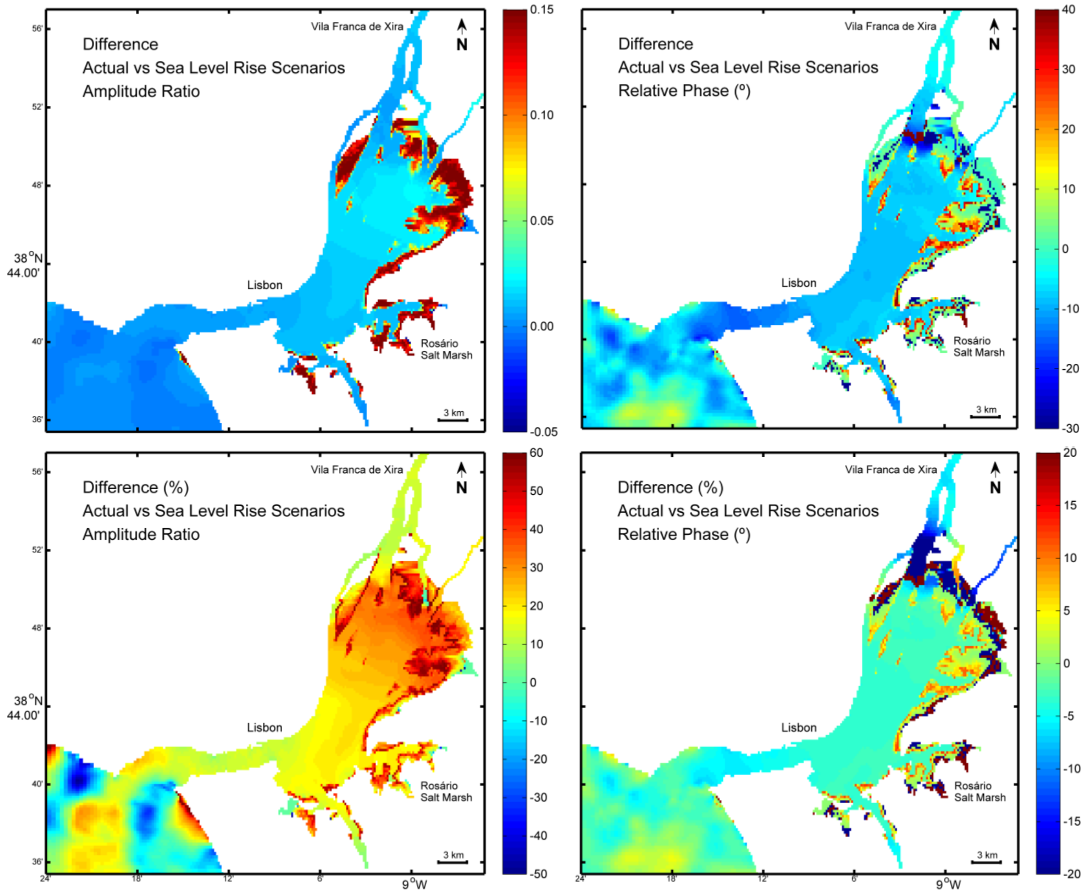

Figure 22: Difference in the tidal asymmetry results (amplitude ratio A_r, on the left; relative phase φ, in degrees (°), on the right) between actual and sea level rise scenarios in Tagus estuary. Difference results are presented in absolute value (upper) and in percentage (base).

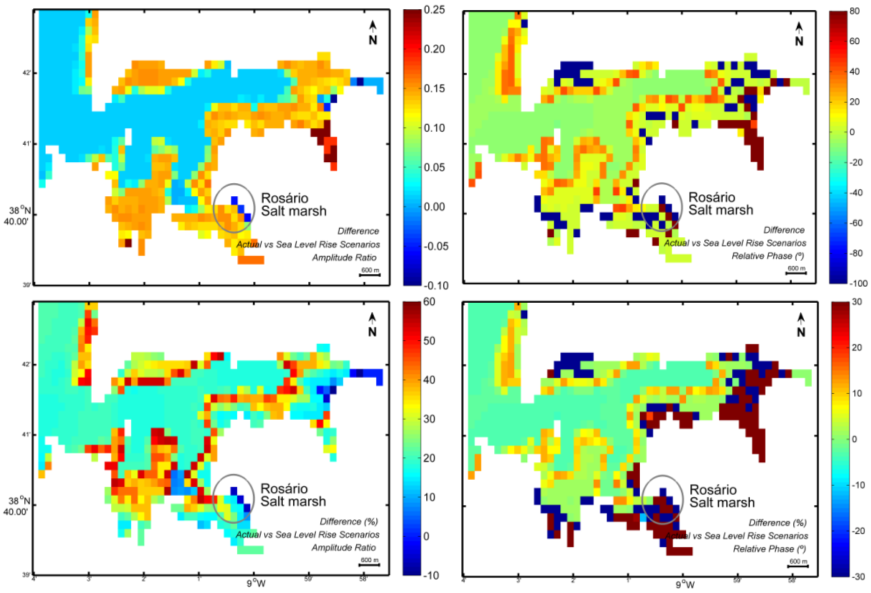

Figure 23: Difference in the tidal asymmetry values (amplitude ratio A_r, on the left; relative phase φ, in degrees (°), on the right) between actual and sea level rise scenarios in Rosário salt marsh (Tagus estuary). Difference results are presented in absolute value (upper) and in percentage (base).

3.2.2. Tidal asymmetry in Ria de Aveiro lagoon

Analysing the tidal asymmetry results for actual and SLR scenarios, the results presented in Figure 24 reveals that in actual scenario, except for the main channels head, the amplitude ratio ranges between 0.03 and 0.06. Espinheiro channel presents the higher values, higher than 0.06. In S.Jacinto channel, A_r decreases within the channel and it is lower than 0.05, excluding the final areas of the channel. With sea level rise, the amplitude ratio decreases, varying now between 0.02 and 0.05, demonstrating that shallow water effects become less important, possible due to the increase of the water column height. The differences between the two scenarios are more evident in the channels in the middle of the lagoon, where for the sea level rise scenario the values are at least 25% lower than for the actual scenario (Fig.26). In the largest area of S.Jacinto channel for example, are found values 80% higher in actual scenario (red colours). Differences are minimal essentially close to the system mouth, once the distortion of the tidal wave increases with the propagation within the system.

Globally, in SLR scenario values decrease about 20% in channels closest to system mouth and 60% in the distant areas (Fig.26).

In Barra salt marsh, in SLR scenarios the A_r values decrease almost 30% (Fig. 27), being 0.04 in actual scenario and approximately 0.03 in SLR (Fig.24). Such as in Rosário, in Barra salt marsh amplitude ratio decrease may be related with the higher water column, that reduce the shallow water effects, and consequently, the ebb dominance. Hence, these results might indicate that flood durations might increase with SLR, which is an important factor for the salt marsh plants.

Regarding the relative phase, according to the model results (Fig.25) there are both ebb (relative phase between 180 and 360º) and flood dominated (relative phase less than 180º) areas in Ria de Aveiro, in accordance with the results presented by Dias (2001) and Picado (2008). This trend is observed in both scenarios, being the central part of the lagoon ebb dominated and the remote zones flood dominated. Figure 26 shows that the differences between the two scenarios are minimal in the areas close to the system mouth, becoming in the largest area of S. Jacinto channels more significant: in SLR, relative phase could decrease 50% in this area. Still, the ebb and flood dominance is not modified with SLR scenarios.

Barra salt marsh is located in an ebb dominated area (Fig.25). In Barra salt marsh, for SLR scenario the values are 3% lower than for actual sea level rise (Fig.27) maintaining the ebb dominance pattern.

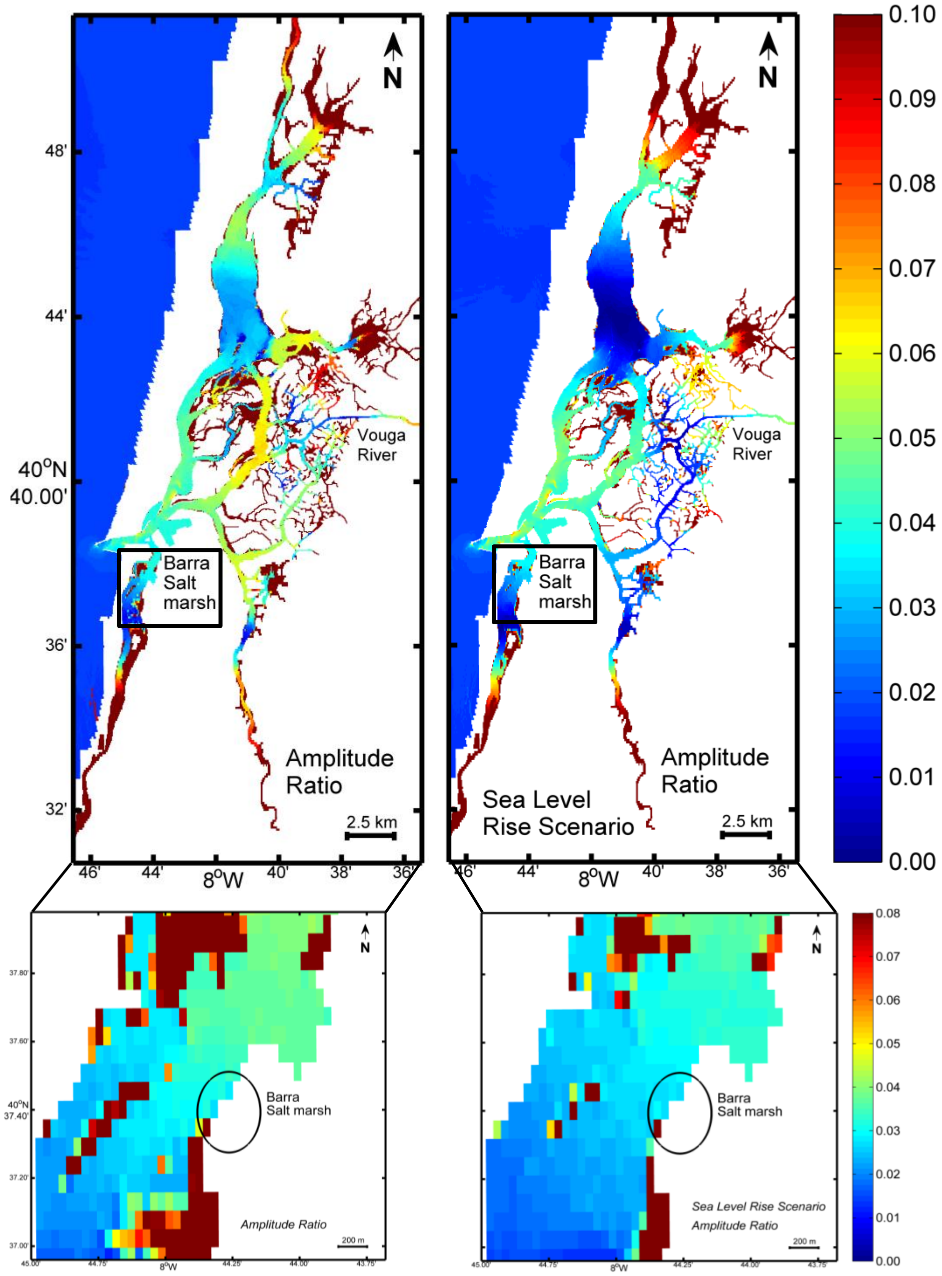

Figure 24: Tidal asymmetry results of amplitude ratio A_r for actual (on the left) and sea level rise scenarios of Ria de Aveiro lagoon and in Barra salt marsh, in detail (base).

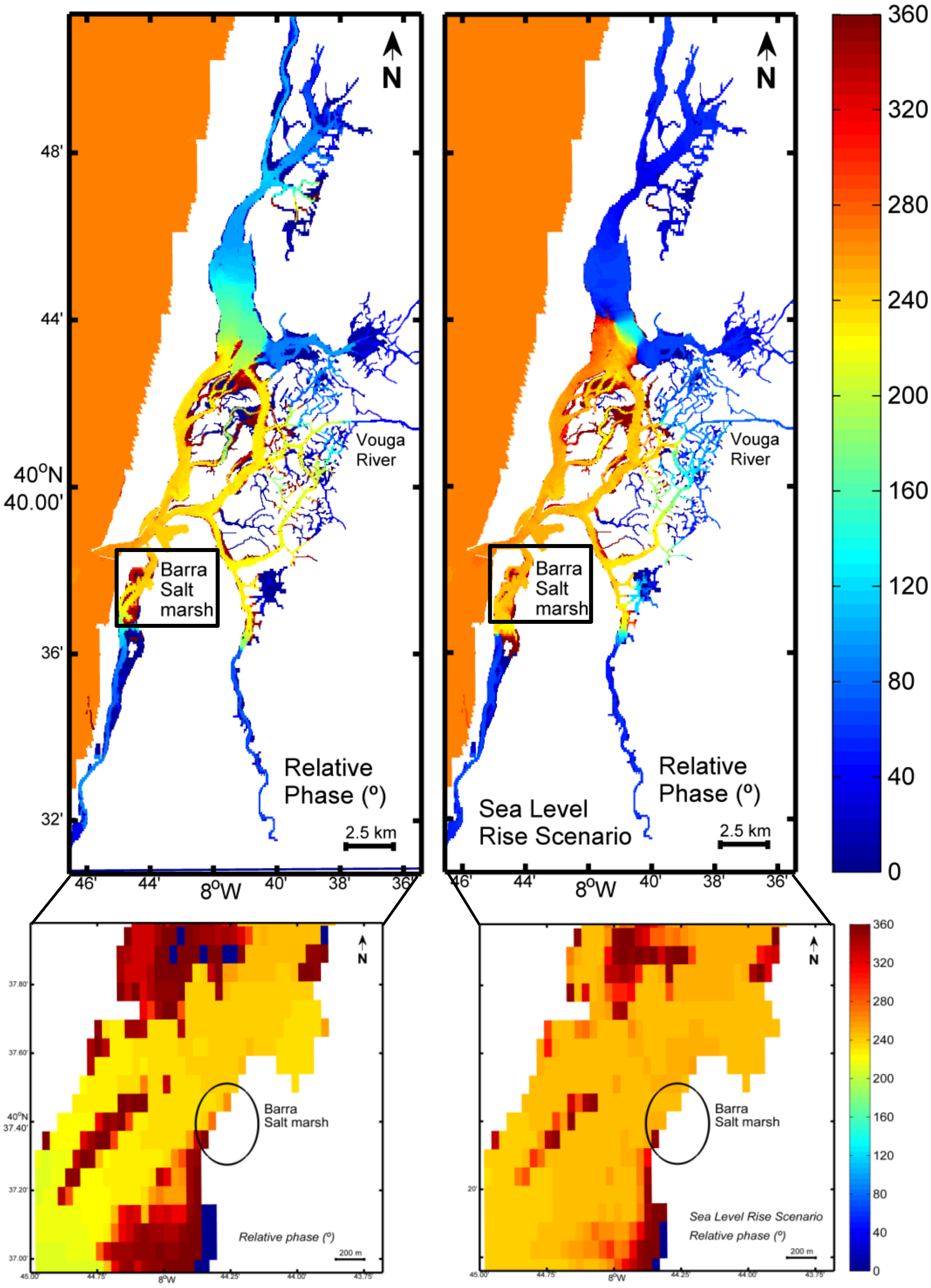

Figure 25: Tidal asymmetry results of relative phase φ, in degrees (°) in Ria de Aveiro lagoon and in Barra salt marsh, in detail (base).

.

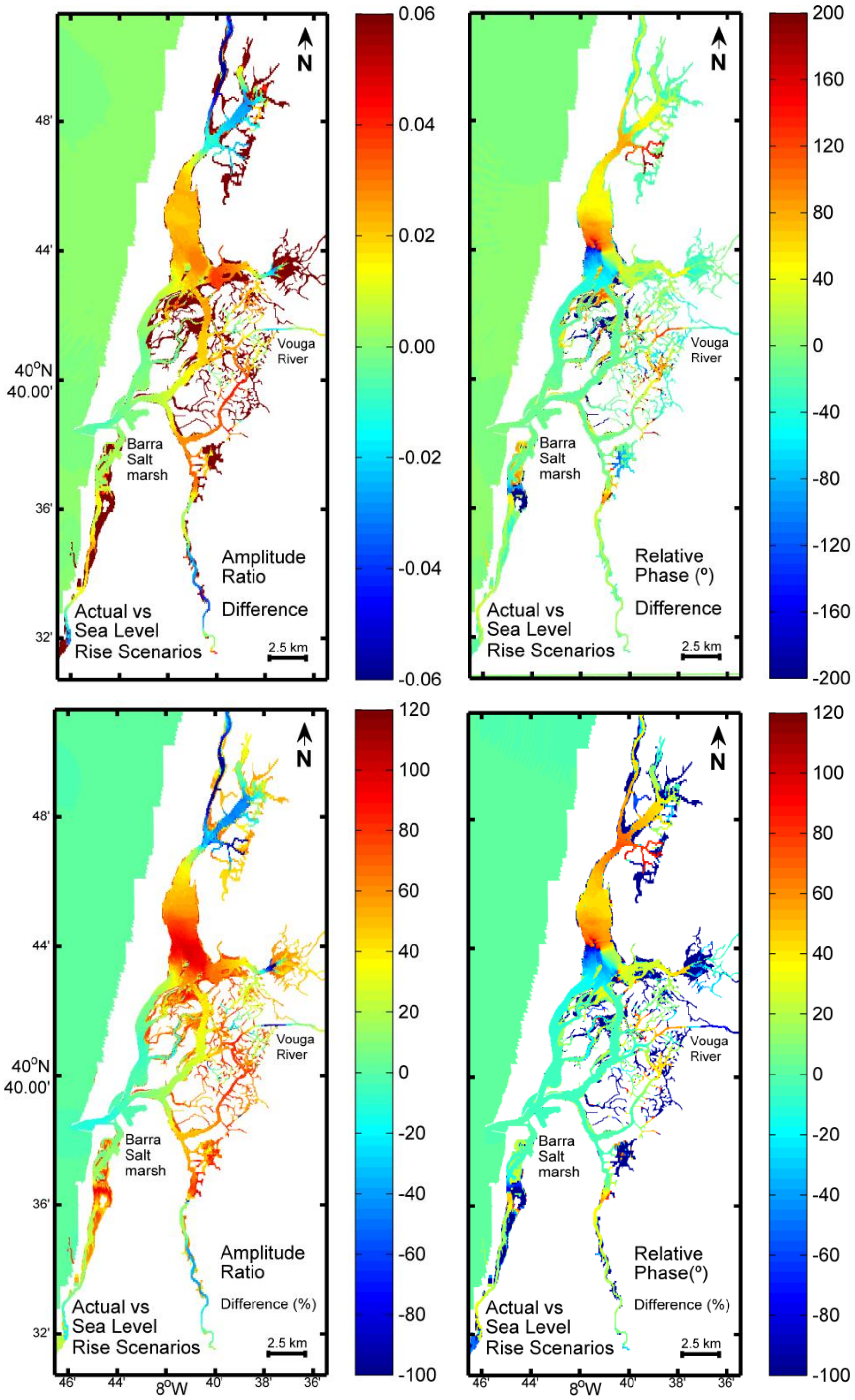

Figure 26: Difference in the tidal asymmetry results (amplitude ratio A_r, on the left; relative phase φ, in degrees (°), on the right) between actual and sea level rise scenarios in Ria de Aveiro. Difference results are presented in absolute value (upper) and in percentage (base).

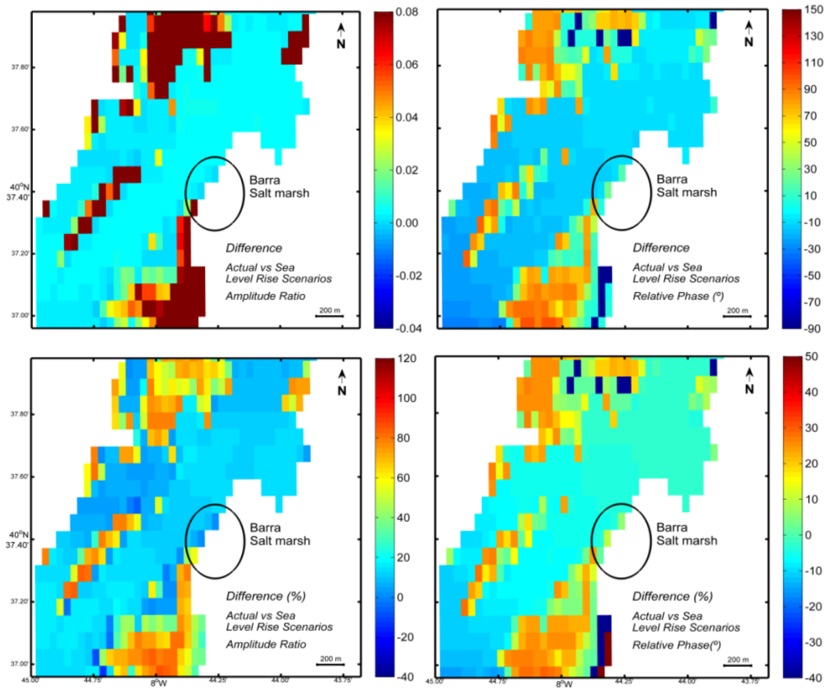

Figure 27: Difference in the tidal asymmetry values (amplitude ratio A_r, on the left; relative phase φ, in degrees (º), on the right) between actual and sea level rise scenarios in Barra salt marsh (Ria de Aveiro). Difference results are presented in absolute value (upper) and in percentage (base).

3.3. Tidal dissipation

3.3.1. Tidal dissipation in Tagus estuary

Figures 28 and 29 show the spatial-logarithmic distribution of the average energy dissipation in neap and spring tides in the Tagus estuary. Energy dissipation values were analysed calculating the logarithm of ε for a better interpretation of results.

Figure 28 indicates that in actual and SLR scenarios, in general, tidal dissipation is higher in spring tides, as expected, once in neap tides tidal currents are weaker. Tidal dissipation is larger in the deepest zones of the estuary, that is, in the main channel (lower estuary) and in the deepest channels of the bay (upper estuary), where the current velocities are higher. In the upper bay, near to the Tagus river mouth, tidal dissipation is higher, possible due to the higher ebbing current that exists in this area due to the freshwater incoming. With the divergence of the bay, the current velocity decrease and therefore, also decrease the tidal dissipation.

According to Figure 28, in actual scenario, energy dissipation is about 0.0120 W/m^2 in spring tides, in the main channel, and 0.004 W/m^2 in neap tides. In the lower bay, these values decrease to 0.0070 W/m^2 in spring tides and 0.0023 W/m^2 in neap tides. These results reveal that tidal dissipation in neap tides is about 30% of the dissipation in spring tides, as observed in Figure 29. Maximum values of 0.0200 W/m^2 are found in the main channel and about 0.0170 W/m^2 are reached in the bay in spring tides. In neap tides, maximum values decreases to 0.0060 W/m^2 (in the main channel) and 0.0040 W/m^2 (in the deepest bay channels) (Fig.28). Without considering the wetting/drying areas, the remaining places in the estuary present green areas that gradually turn to blue tones, close to minimal dissipation, suggesting that dissipation decreases progressively with depth decreasing.

Generally, in sea level rise scenario (Fig.28), energy dissipation is about 0.0140 W/m^2 in spring tides and 0.0048 W/m^2 in neap tides in the main channel. In the lower bay, these values decrease to 0.0078 W/m^2 in spring tides, and to 0.0027W/m^2 in neap tides. These results reveal that for SLR scenarios the tidal dissipation in spring tide is about 14% higher relatively to the actual scenario, while for neap tide it is around 20% higher (Fig.29). The higher water column due to the SLR scenario will induce higher current velocities, as such, tidal dissipation increase. However, in the upper bay, near to freshwater sources, tidal dissipation decreases almost 20% in SLR scenario (Fig.29). This pattern may be explained by the higher tidal flooding due to the increase in water column height that balances the rivers inflow, promoting a weaker ebbing current in those areas comparatively to the actual scenario.

Regarding to Rosário salt marsh results, from Figures 30 and 31, it is observed that in neap tide there are differences around 10% between the two scenarios (with tidal dissipation values being 10% lower in sea level rise scenario (close to 7.4 x 10^{-5} W/m^2) relatively to actual scenario (about 8.4 x 10^{-5} W/m^2)). In spring tide, differences for this salt marsh are 8% (with tidal dissipation values being 8% lower in sea level rise scenario (around 2.3 x 10^{-4} W/m^2) than in actual scenario (approximately 2.5 x 10^{-4} W/m^2)). In this case, tidal dissipation will decrease with SLR once the water column height increase and, therefore, bottom friction effect is minor and, consequently, tidal dissipation decrease.

Summarizing, in SLR scenario, the patterns remain unchanged but, globally, tidal dissipation values increase (i.e., higher in SLR in both neap and spring tide situations). Figure 29 suggests that shallowest areas are the more affected, with differences that can be higher than 40 %. In the main channel and lower bay, tidal dissipation could be around 15% higher in SLR scenario. However, in the upper bay, near to freshwater sources, values decrease almost 30% in SLR scenario, which could be explained by the rivers effects.

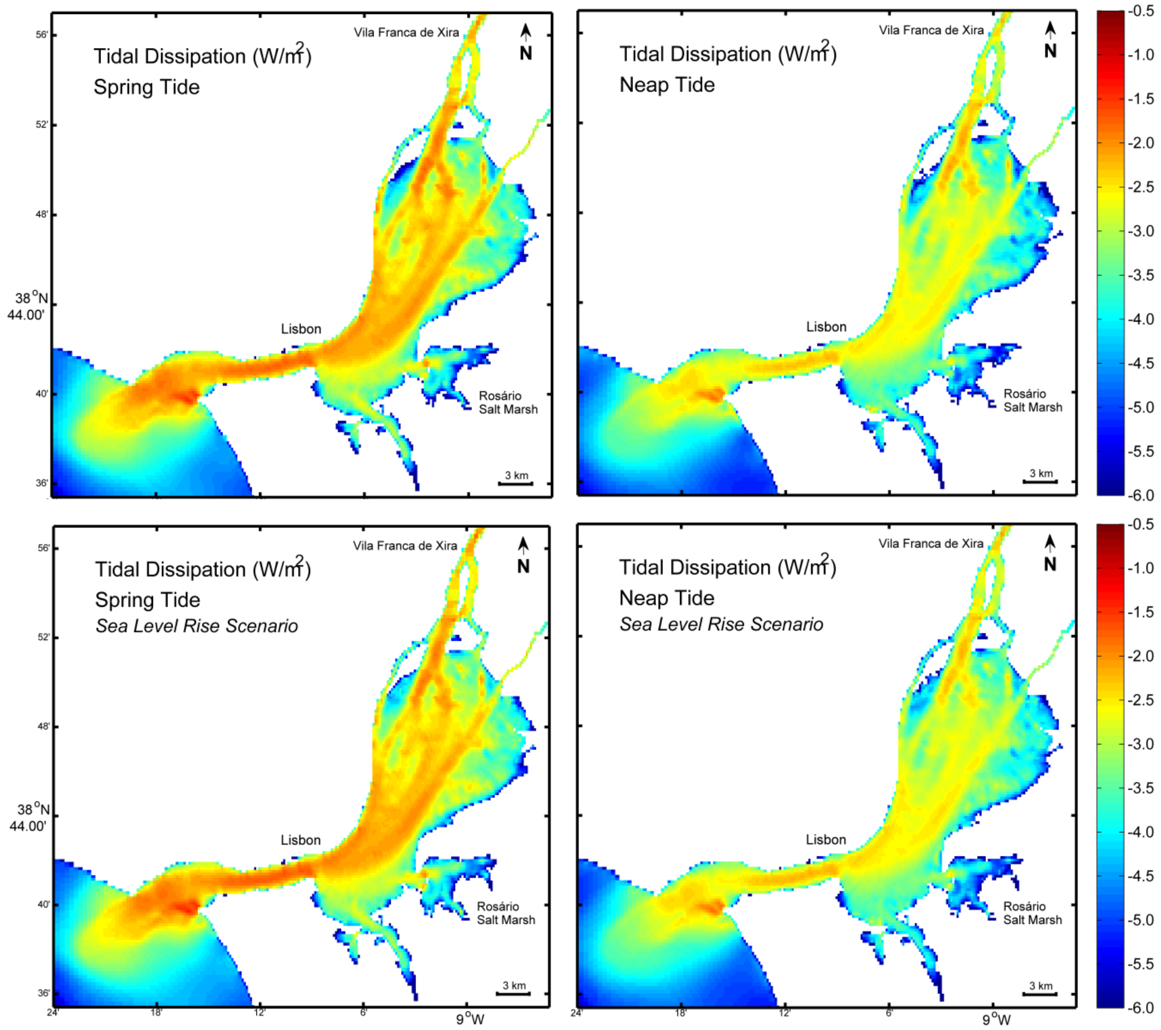

Figure 28: Tidal dissipation results (W/m^2) for actual (upper) and sea level rise scenarios (base) in Tagus estuary. On the left are presented the Spring Tide values and on the rigth are displayed Neap Tide. For a better interpretation, the results are presented in *$log_{10}\varepsilon$*.

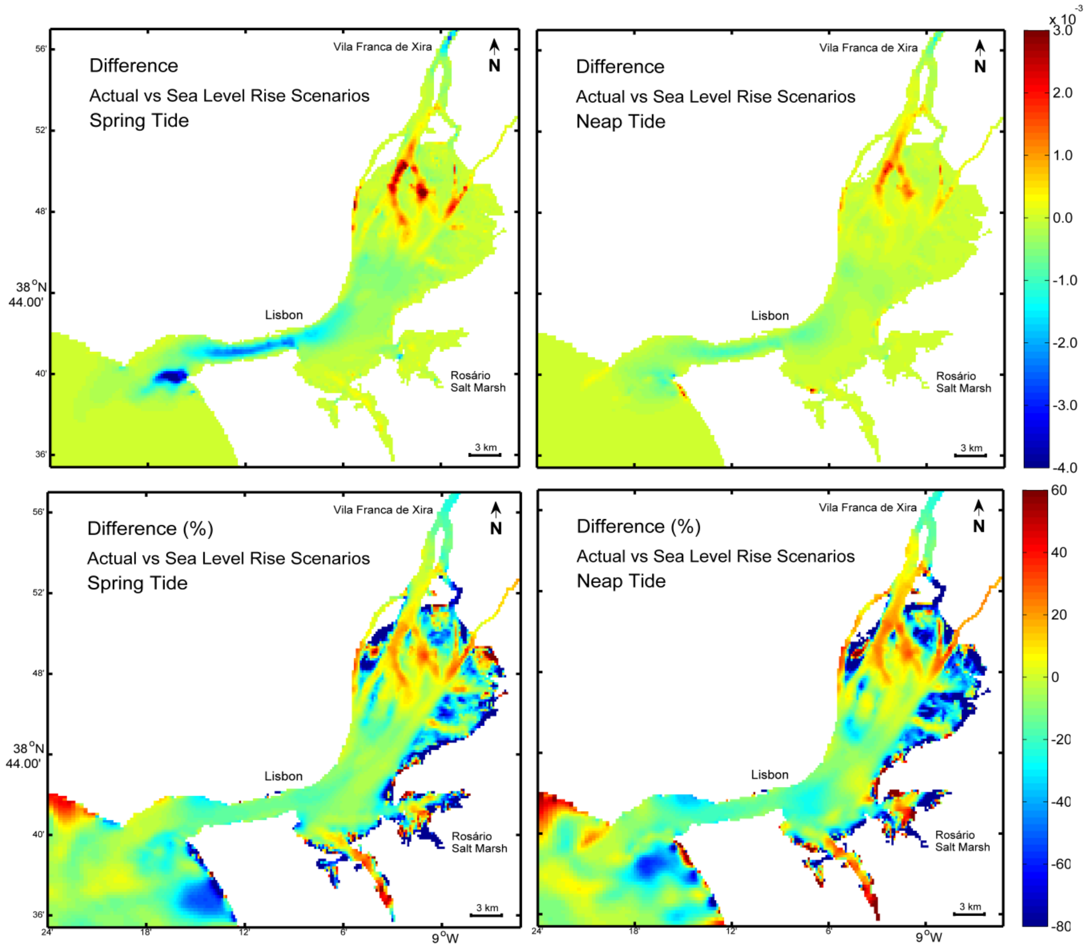

Figure 29: Differences of tidal dissipation results between actual and sea level rise scenarios in Tagus estuary. On the left are presented the Spring Tide values and on the rigth are displayed Neap Tide values.

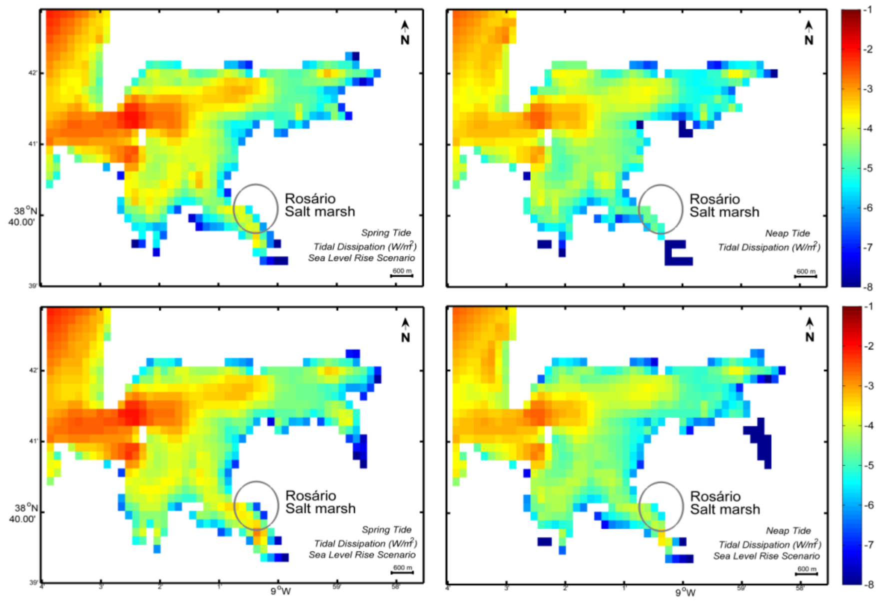

Figure 30: Tidal dissipation results (W/m^2) for actual (upper) and sea level rise scenarios (lower) in Rosário salt marsh (Tagus estuary). On the left are presented the Spring Tide values and on the rigth are displayed Neap Tide. Results are presented in $log_{10}\,\varepsilon$.

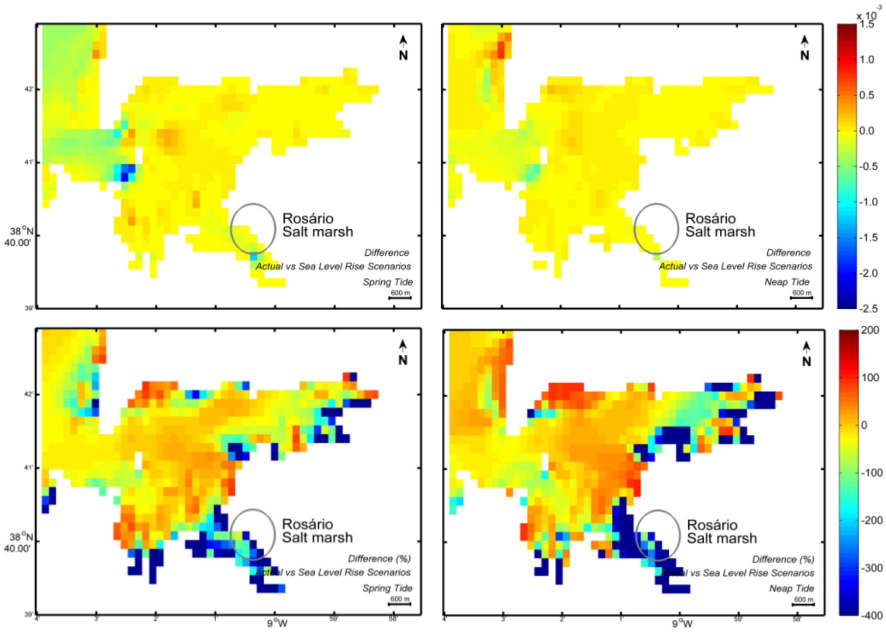

Figure 31: Differences in absolute value (upper) and in percentage (base) of tidal dissipation values between actual and sea level rise scenarios in Rosário salt marsh (Tagus estuary). On the left are presented the Spring Tide values and on the rigth are displayed Neap Tide values.

3.3.2. Tidal dissipation in Ria de Aveiro lagoon

Figures 32 and 34 show the spatial-logarithmic distribution of the average energy dissipation in neap and spring tides in the Ria de Aveiro lagoon, both for the entire system as for the Barra salt marsh area, respectively. Once again, energy dissipation values were analysed calculating the logarithm of ε for a better interpretation of results.

In general, in both scenarios, results indicate that tidal dissipation is higher in spring tides, as expected, due to the weaker tidal currents found on neap tides which lead to a smaller energy dissipation (Fig.32).

Maximum values of tidal dissipation are founded in the lagoon mouth, Espinheiro and S.Jacinto channels: 0.592 in neap tides and 1.692 W/m^2 in spring tides, in actual scenario; 0.864 in neap tides and 2.296 W/m^2 spring tides, in SLR scenario (Fig.32). Moreover, taking to account Figure 33, these results suggest that, in those places, tidal dissipation in SLR scenarios present values about 35% (spring tides) and 45% (neap tides) higher relatively to actual scenario. The remaining areas of the lagoon (green to yellow colours) present tidal dissipation values between and 0.010 and 0.100W/m^2 (except the narrow shallowest channels where tidal dissipation is minimum, as represented by the dark blue colours – tidal dissipation values lower than 0.003 W/m^2).

In the complex central areas of the lagoon, including the net of narrow and shallow water channels near Vouga and Antuã rivers, tidal dissipation decrease in SLR scenario (Fig.33). The current velocity in those areas induced by the rivers inputs found in actual scenario could be balanced by the elevation of the water column height due to the SLR, which could reduce the current velocity in those places. Therefore, tidal dissipation decreases.

Regarding to the Barra salt marsh area (Figs. 34 and 35), it was observed that in neap tide differences of 11% between the two scenarios were founded (with tidal dissipation values being 11% lower in sea level rise scenario (close to 0.034 W/m^2) relatively to actual scenario (about 0.038 W/m^2)). In spring tide, Barra salt marsh presents differences of 18% (with tidal dissipation values being 18% lower in sea level rise scenario (approximately 0.032 W/m^2) than in actual scenario (around 0.039W/m^2).

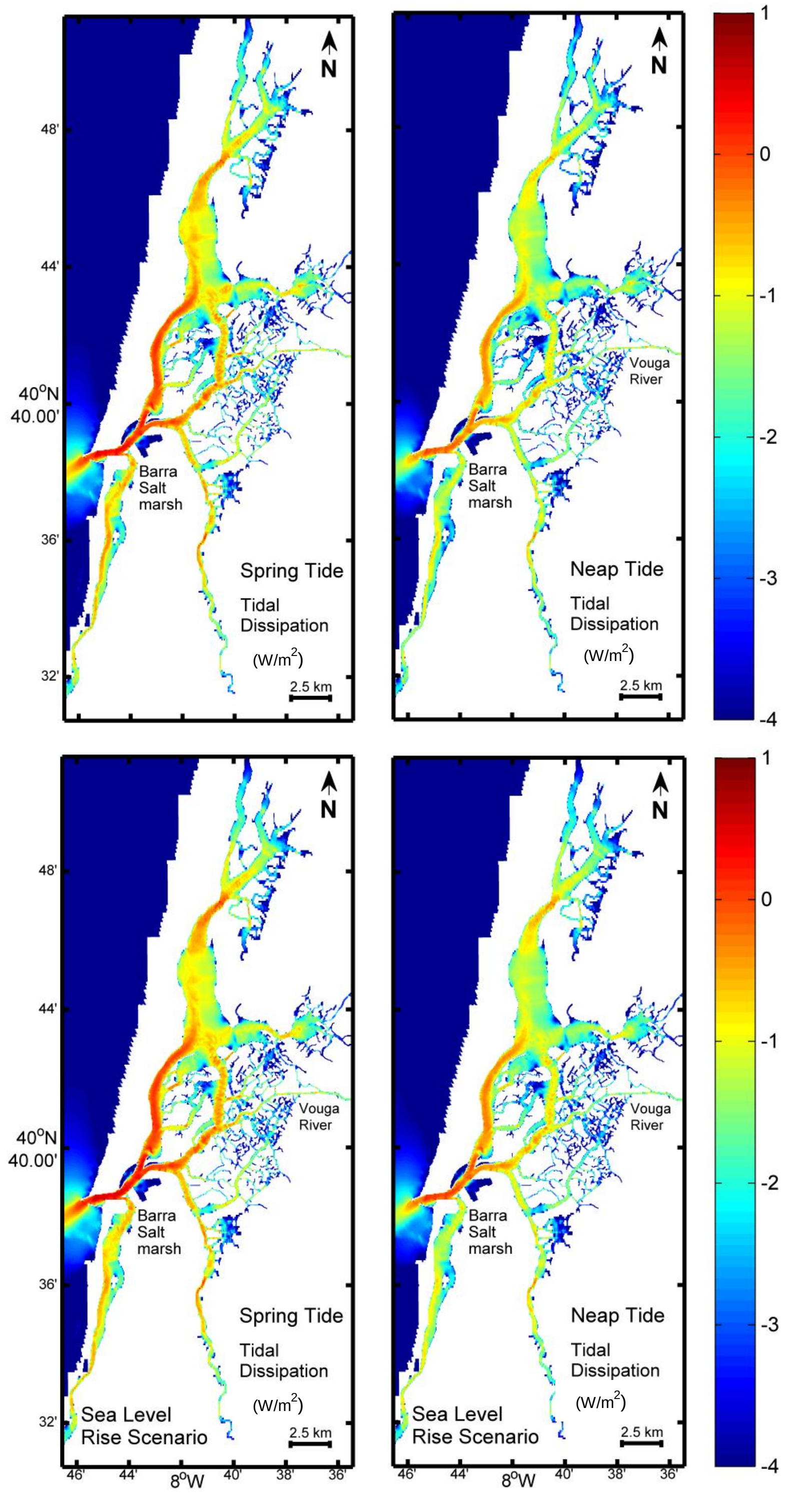

Figure 32: Tidal dissipation results (W/m^2) for actual (upper) and sea level rise scenarios (base) in Ria de Aveiro lagoon. On the left are presented the Spring Tide values and on the rigth are displayed Neap Tide values. For a better interpretation, the results are presented in $log_{10}\,\varepsilon$.

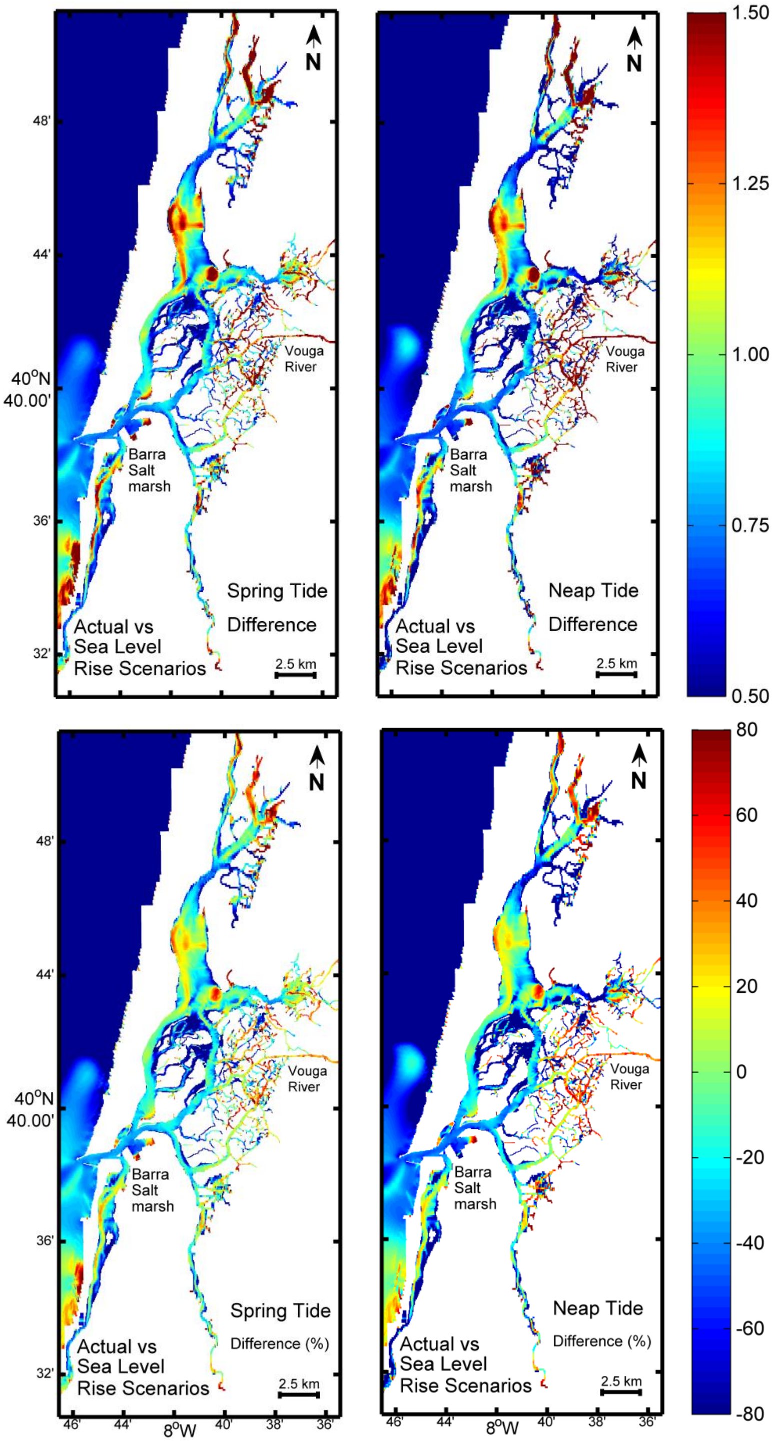

Figure 33: Differences in absolute value (upper) and in percentage (base) of tidal dissipation values between actual and sea level rise scenarios in Ria de Aveiro lagoon. On the left are presented the Spring Tide values and on the rigth are displayed Neap Tide values.

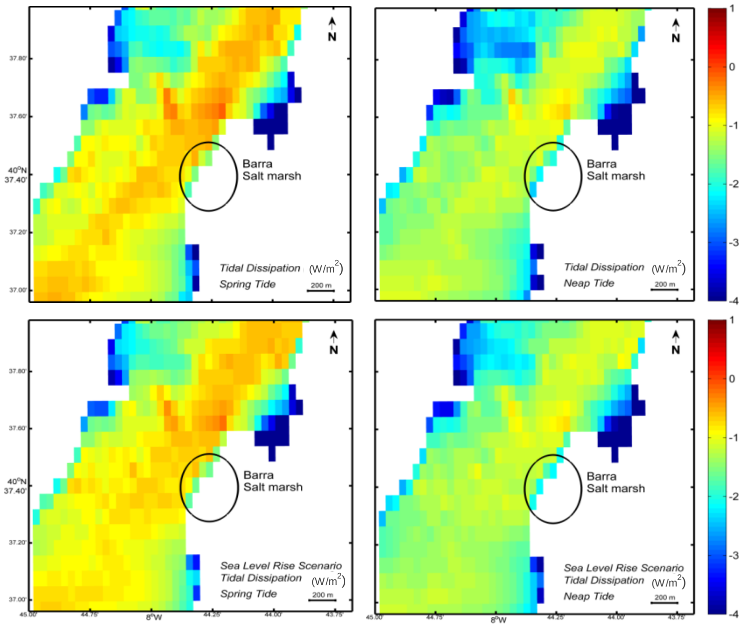

Figure 34: Tidal dissipation results (W/m^2) for actual (upper) and sea level rise scenarios (base) in Barra salt marsh (Ria de Aveiro lagoon). On the left are presented the Spring Tide values and on the rigth are displayed Neap Tide tidal dissipation results. For a better interpretation, the results are presented in *log_{10} ε*.

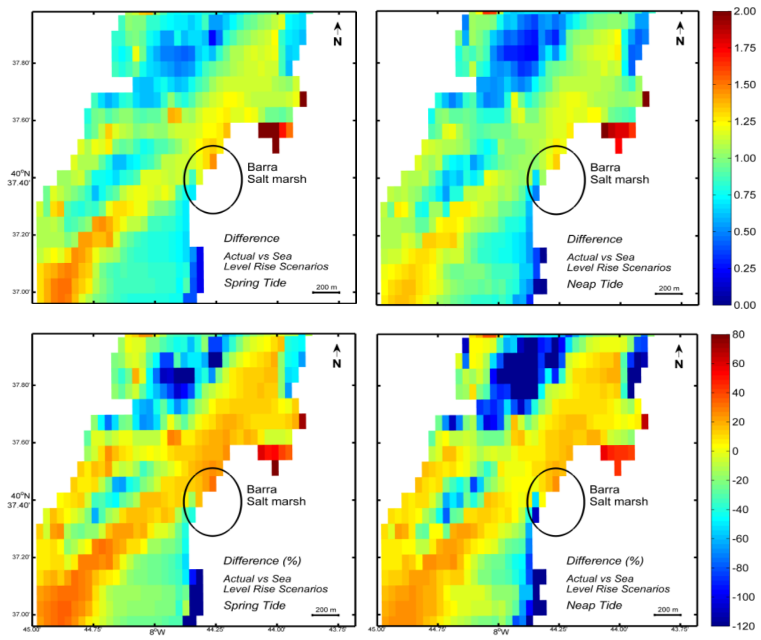

Figure 35: Differences in absolute value (upper) and in percentage (base) between actual and sea level rise scenarios in Barra salt marsh (Ria de Aveiro lagoon). On the left are presented the Spring Tide values and on the rigth are displayed Neap Tide tidal values.

3.4. *Spartina maritima*

Many authors have referred the important role of vegetation in the consolidation of salt marsh sediments, but the particular and unique conditions of each salt marsh must be considered in the study of the role of vegetation in the stabilization and survival of these areas (Silva *et al.*, 2009).

Saltmarsh processes are very dependent on abiotic factors, such as salinity, which in turn depend on a great variety of conditions, like the extent and frequency of tidal flooding, evapotranspiration and vegetation. The tidal regime contributes very strongly to the heterogeneity of salt marshes, once it affects chemical and physical factors, such as salinity and nutrient concentration. Environmental stress, i.e. salinity and flooding, may induce species to develop resistance mechanisms, thus adapting to the environment during their evolution (Vernberg 1993).

Some works show that *S. maritima* above and belowground production is influenced and determined by physicochemical characteristics, such as soil salinity, tidal inundation, nutrient availability, oxygen levels, drainage, sediment type, maturity of the salt marsh, among others. Thus, *S. maritima* productivity depends on the complex interaction of all these factors, which inherently varies according to the particular characteristics of each salt marsh (Ibañez et al., 2000; Sousa *et al.*, 2009a, 2010).

The following table indicates the results for the parameters analysed in both salt marshes relatively to *S.maritima*.

Table 1: *S.maritima* results (mean values; n=3) for Barra (Ria de Aveiro) and Rosário (Tagus estuary) salt marshes for the different parameters studied.

	Barra salt marsh				**Rosário salt marsh**			
	Spring	**Summer**	**Autumn**	**Winter**	**Spring**	**Summer**	**Autumn**	**Winter**
Organic matter (%)	10.5	16.5	11.1	12.2	23.0	19.6	23.4	18.1
Sediments moisture (%)	47.9	39.4	50.4	51.2	8.1	21.5	35.1	33.3
Ratio below/aboveground biomass (kg/m^2)	14.2	14.7	10.1	13.9	8.1	13.7	5.9	7.4
Vegetation coverage (%)	19	19	19	19	12	12	12	12

For a better interpretation of Table 3, the hydrodynamic results for each of salt marshes should be considered. Summarizing, residual circulation is higher in Barra salt marsh than in Rosário. With SLR scenarios, model results suggest that residual circulation will increase in Rosário, but will decrease in Barra salt marsh. Concerning tidal asymmetry, the amplitude ratio is higher in Rosário. In SLR scenarios, A_r values decrease in both salt marshes. Also, both salt marshes are located in an ebb dominance area. The amplitude ratio decreasing could indicate a lower tendency for ebb dominance, therefore flood durations might increase. Consequently, the inundation period in these salt marshes may increase. Finally, tidal dissipation is considerably higher in Barra salt marsh than in Rosário. In SLR scenarios, tidal dissipation will decrease in both salt marshes.

In salt marshes, the nature of any tidal asymmetry is significant in determining the delivery of sediments (Townend *et al*., 2012). Rosário and Barra salt marshes are ebb dominant, which encourage the export of sediments, but lower values of amplitude ratio were found in Barra salt marsh. This situation could indicate a lower tendency for ebb dominance in Barra than in Rosário salt marsh and, therefore, higher flood duration can occur. This scenario might justify the elevate sediment moisture in Barra salt marsh (Table 3).

The higher values of sediment moisture at Barra may be responsible for the increase of the physiological stress of *S.maritima*. This situation could leads to *S. maritima* attempt adaptation by investing in the belowground biomass as referred by Sousa *et al*. (2009a; 2010), once the development of belowground biomass is enhanced by halophytes under environmental stress like tidal inundation. Therefore, the ratio below/aboveground biomass could function as an indicator revealing which salt marsh is under more stress conditions, where the plant belowground biomass investment is higher. In fact, the apparent higher stress conditions of Barra salt marsh, indicated by the higher values of sediment moisture, could explain the higher ratio of below/aboveground biomass found in this salt marsh (Table 3).

Moreover, the higher values of residual circulation and lower tidal dissipation found in Barra salt marsh relatively to Rosário suggest a trend to erosion and resuspension at Barra. This situation may be responsible for the exportation of sediment which could explain the lower values of organic matter found in this salt marsh (Table 3).

The higher organic matter at Rosário may be responsible for the upstream establishment of other dominant species, such as *H. portulacoides* and *S. perennis*, therefore reducing the coverage percentage of *S.maritima* at this salt marsh, as shown by the results on Table 3. These results are in accordance with the “competition-to-stress hypothesis”, referring that the upstream limits of plant distributions are determined by competition, and the downstream limits by abiotic stress, namely flooding. According to Bertness *et al.* (1992) and Pennings and Bertness (2001) competitive dominants (e.g. *H. portulacoides*) are typically unable to survive in physically harsh conditions (e.g. frequent flooding), while stress-tolerant, but competitively subordinate plants (e.g. *S.maritima*) grow in more stressful habitats because they are displaced from less stressful habitats by dominant competitors. However, studied species may have a physiological requirement for some nutrients for optimal growth, which may be scarce in upstream conditions (Guo and Pennings, 2012).

Analysing the hydrodynamic values in SLR scenario, according to the model results, residual circulation will decrease in Barra and increase in Rosário salt marsh. This increase in Rosário indicates a decrease in the residence time and consequently could increase the water properties renovation. This situation may induce changes in the nutrients and sediments patterns and, thus, the percentage of vegetation coverage will be probably affected once production and salt marsh zonation are affected by nutrients and sediments availability, which is associated, among other factors, with sea level rise (Valiela and Teal, 1974; Townend *et al.*, 2011). In fact, nutrients and environmental characteristics, such as sediments inputs and seawater inundation, are major contributors to production and zonation of salt marsh vegetation (Fox *et al.*, 2012).

According to Reed *et al*. (1999), halophyte vegetation is very sensitive to the inundation frequency and the persistence of these coastal wetlands depends upon sediment deposition that controls the vertical position of the marsh surface. Also, tidal inundation affects the salt marsh plants distribution. Moreover, the proportion of sand and mud deposited, which can change the nature of salt marsh plant community by altering the drainage conditions, is related with sediment supply and also with tidal inundation (Townend *et al,* 2011). In this study, SLR model results also show a decrease in tidal asymmetry amplitude in both salt marshes, probably due to the increase in the water column height associated to the SLR scenario, reducing the shallow water effects and consequently the wave distortion. This situation will decrease the ebb dominance tendency and, as such, will increase the flood duration. Therefore, sediment moisture might increase causing a stress condition to the plants and, in turn, the ratio below/aboveground biomass could increase and this rate is critical to their survival under conditions of accelerated sea level rise (Cahoon *et al.*, 2004; Townend *et al.,* 2011)

Finally, model results indicate that tidal dissipation will decrease in both salt marshes, due to the reduction of the bottom friction effects induced by the higher water column height. This situation may reduce the dynamics of these areas and, consequently, decrease sediment resuspension which, in terms of abiotic conditions, may cause an increase in organic matter contents and deposition.

In general, processes that tend to increase the local concentration of suspended sediments will increase the minerogenic contribution to accretion. Therefore, tidal velocity, increased coastal erosion and changes in tidal asymmetry may all alter the availability of sediment (Friendrichs and Perry, 2001; Townend *et al.*, 2011).

According to Townend *et al.* (2011), there is considerable evidence that marsh morphology is close to equilibrium over time scales of decades to a few centuries which indicates their ability to rapidly respond to changes in the forcing conditions. However, it is expected a sea level rise at a higher rate during the 21th century, which represents an uncertain in the salt marsh response to this threat.

The alterations in the SLR scenarios demonstrated by the model results indicate that some abiotic features could be modified and, once salt marsh plants depend on these parameters, their present status could be affected. However, this approach only presents the possible changes based on some of the large number of factors that influence salt marsh plants. In fact, it is necessary to remember that salt marshes processes are governed by physical, geological, and chemical factors, biotic factors (including productivity of vascular plants, phytoplankton, epibenthic algae; secondary production of primary and secondary consumers; and decomposition), biogeo-chemical cycling and the interaction with adjacent ecosystems (Vernberg, 1993). Therefore, the model results presented in this study give only some indications about what could happen in a climate change scenario.

4. Conclusions

All the proposed objectives for this work were achieved. The model results allowed to understand the general patterns of the residual circulation, tidal asymmetry and tidal dissipation in Tagus estuary and in Ria de Aveiro lagoon, both in actual mean sea level and sea level rise scenarios. The exploration of the SLR results indicates how the systems will evolve in this scenario, showing that the hydrodynamic parameters in study will suffer important changes under climate change context. Moreover, the *S.maritima* results suggest that the hydrodynamic parameters might explain the different plant characteristics found in each salt marsh, as a response to the different conditions.

For Tagus estuary, results showed that rivers discharges effect cannot be unconsidered in the long term system's hydrodynamic analysis, once residual currents intensity could be 40% higher in *Typical* inflow than in *No Discharges* scenario and can even be 100% higher in *Maximum* inflow scenario. The SLR scenario induces a significant decrease in residual circulation in this estuary. Although residual circulation slightly increases in some areas of the estuary mouth, it decreases almost 30% in *Typical Discharges* and 10% in *Maximum Discharges* in the bay.

Also, in Ria de Aveiro lagoon, the rivers inputs represent an important forcing for the long term processes. Face to *No Discharge* scenario, residual circulation is about 20% higher in *Typical Discharges*. *Maximum Discharge* means an increase of at least 60% in the residual circulation in most system comparing to *Typical Discharges*, which confirms the significant influence of rivers discharge in the general circulation of the lagoon. In Tagus estuary the river inflow has a higher effect, mostly in the upper bay, near to the river mouth. However, in Ria de Aveiro lagoon, probably due to its complex morphology and to the large number of inflowing rivers, their impact seems to have a more global effect, once it influences extends far from the rivers' mouth reaching the areas close to the lagoon's mouth. In SLR scenario, results indicate a decrease of residual circulation in the entire lagoon, approximately 20% and 15% in *Typical* and *Maximum*, respectively.

In both systems, residual circulation's direction is outward, revealing the trend of these estuaries to export sediments, nutrients and organic matter. Considering the predicted changes in this hydrodynamic parameter, long-term transport in the estuaries could be altered and therefore the surrounding ecosystems might be affected, once residual circulation is a key parameter in the dynamical behavior of coastal systems.

The tidal asymmetry results show that the amplitude ratio increases progressively within Tagus estuary, except in the upper bay, for both actual and SLR scenarios. Regarding the relative phase, as expected, Tagus estuary is ebb dominant, which is observed in both scenarios. In Ria de Aveiro lagoon, Espinheiro channel presents the highest values for the amplitude ratio. With sea level rise, globally, values decrease about 20% in the channels closest to system's mouth and 60% in the distant areas. According to the model results, there are both ebb and flood dominated areas in the lagoon. In fact, the central area of the lagoon in ebb dominated, while the channels heads are flood dominated, which is in accordance with results presented previously by other authors. This trend is observed in both scenarios.

The amplitude ratio reduction in both systems in the SLR scenario may be explained by the decrease of the shallow water effects, due to the increase of the water column height. Therefore, the amplitude of M_4 was found less important and consequently, the amplitude ratio decreases. Tidal asymmetry is frequently the dominant factor in causing net sediment transport and deposition, resulting in sediment trapping in coastal areas and estuaries, which is an important factor for salt marsh plants development. Once ebb dominant conditions lead to a seaward transport, Tagus estuary presents a net exportation behavior, while Ria the Aveiro lagoon presents both exportation and importation areas.

Moreover, following the amplitude ratio decreases in SLR scenario, in Tagus estuary the ebb dominated tendency will decrease and consequently, the flood duration will increase. In the Ria the Aveiro lagoon, this will also occur in the ebb dominated areas, while the opposite will occur in the flood dominated areas. Changes in the tidal asymmetry are an important issue, once this parameter has essential implications also in the water contaminants dispersal, on geological time scales and estuarine stability, among others.

Like residual circulation and tidal asymmetry, the tidal dissipation results demonstrate the rule of the systems morphology and topography, as well as the importance of the rivers inflow and tidal forcing balance in the estuaries hydrodynamics. Tidal dissipation is higher in spring tides, in the deepest zones of both systems, where the tidal current's velocity is stronger. In Tagus estuary, tidal dissipation increases about 14% and 20% in spring and neap tides, respectively, in SLR scenarios, possible due to the higher water column that induces higher currents velocity. However, tidal dissipation decreases about 20% in the upper bay, probable due to the effects of Tagus river discharges. In Ria de Aveiro lagoon, tidal dissipation is much higher than in Tagus estuary, possible because of the lower depth of most of its channels that make the bottom friction more important, promoting a higher energy dissipation. In SLR scenario, tidal dissipation present values about 35% (spring tides) and 45% (neap tides) higher relatively to actual scenario.

The hydrodynamic model results could be further explored in the frame of different research topics. Considering the main objectives of this work, the model results interpretation was conducted considering essentially the salt marshes dynamics. As future studies, these results may be additionally analysed in order to complete the information about the hydrodynamic patterns in the Tagus estuary and Ria de Aveiro lagoon, namely the possible effects of the SLR in this patterns.

Regarding to the salt marshes analysis, results suggest that the studied hydrodynamic parameters might explain the different characteristics found for *S.maritima*, namely the belowground biomass, as a response to the different conditions.

The apparent higher stress conditions of Barra salt marsh, due to the higher values of sediment moisture found here, could explain the higher ratio of below/aboveground biomass reported in this salt marsh, once a stress situation could leads to *S. maritima* attempt adaptation by investing in the belowground biomass.

The lower values of organic matter found in Barra could be explained by the higher trend to erosion and resuspension in this salt marsh, due to the higher values of residual circulation and lower tidal dissipation. The higher organic matter at Rosário may be responsible for the upstream establishment of other dominant species, such as *H. portulacoides* and *S. perennis*, therefore reducing the coverage percentage of *S.maritima* at this salt marsh. This pattern is in concordance with the "competition-to-stress hypothesis", referring that the upstream limits of plant distributions are determined by competition and the downstream limits by abiotic stress, namely flooding.

In SLR scenario, residual circulation, tidal asymmetry and dissipation present differences that, interacting with other factors, might represent a stress factor to the biologic communities that exist in those systems and are adapted to the present hydrodynamic conditions.

According to the model results, residual circulation will decrease in Barra and increase in Rosário salt marsh in sea level rise context. This increase in Rosário indicates a decrease in the residence time and consequently could increase the water properties renovation. This situation could lead to changes in the nutrients and sediments patterns and, thus, the percentage of vegetation coverage would be probably affected, once production and salt marsh zonation are affected by nutrients and sediments availability, which is associated, among other factors, with sea level rise.

In this study is demonstrated that SLR also induces a decrease in amplitude ratio in both salt marshes. This situation might decrease the ebb dominance tendency and, as such, will increase the flood duration. The sediment moisture might increase causing a stress condition to the plants and, in turn, the ratio below/aboveground biomass could increase, and this rate is critical to their survival under conditions of accelerated sea level rise.

Finally, results indicate that tidal dissipation will decrease in both salt marshes, which may reduce the dynamics of these areas and, consequently, decrease sediment resuspension which, in terms of abiotic conditions, may cause an increase in organic matter contents and deposition.

The expected sea level rise in response to climate changes represents an uncertain in the salt marsh future development and stability. The alterations in the SLR scenario predicted in this study indicate that some abiotic features could be modified and, once salt marsh plants depend on these parameters, their present status could be affected. However, this approach only presents the possible variation of some of the many factors that influence salt marsh plants development and it is also necessary to considerer the interaction between those factors. The results give only some indications of what could happen in a climate change scenario. Therefore, as future work, a more complete approach should be performed in order to support and complete these results. The application of a biogeochemical model, with the possibility to include others parameters that could help to complete this analysis, will represent an important tool that certainly will help to improve the knowledge about the different processes occurring in these areas.

5. References

Ahmad, I., Mohmood, I., Coelho, J.P., Pacheco, M., Santos, M.A., Duarte, A.C., Pereira, E., 2012. Role of non-enzymatic antioxidants on the bivalves' adaptation to environmental mercury: Organ-specicities and age effect in *Scrobicularia plana* inhabiting a contaminated lagoon. *Environmental Pollution,* **163**, 218 – 225.

Aldridge, J.N., 1997. Hydrodynamics model predictions of tidal asymmetry and observed sediment transport paths in Morecambe Bay. *Estuarine, Coastal and Shelf Science*, **44**, 39-56.

Alves, F.L., Silva, J.V., Pereira, C.A., Sousa, L.P., 2011. Ten Years Assessment of ICZM Principles Applied at a Local Scale: Ria de Aveiro Case Study. *Journal of Coastal Research*, **64**, 1311-1315.

Ambar, I., Backhaus, J., 1983. A bidimensional numerical model of circulation in the Tejo Estuary. Comunicação apresentada na Conferência Nacional de Física, Évora.

Anjos, D., Fernandes, R., Lino, S., Pita, G., Neves, R., 2003. Modelação Operacional no Estuário do Tejo – REALTIME (Acoplamento de um Modelo e de um Sistema Automático de Aquisição de Dados). In: VII Congresso Nacional de Engenharia do Ambiente. Lisboa, Portugal.

Anjum, N.A., Ahmad I., Válega, M., Pacheco, M., Figueira, E., Duarte, A.C., Pereira, E., 2012 (in press). Salt marsh macrophyte *Phragmites australis* strategies assessment for its dominance in mercury-contaminated coastal lagoon (Ria de Aveiro, Portugal). *Environmental Science and Pollution Research.*

Arantes e Oliveira, E., 1941. Esgotos de Lisboa – Estudos de Ante Projecto. Trabalho elaborado para a Câmara Municipal de Lisboa.

Araújo, I.B., 2005. *Sea Level Variability: Examples From the Atlantic Coast of Europe*. PhD Thesis, School of the National Oceanography Centre, Southampton, UK.

Araújo, I.B, Dias, J.M., Pugh, D.T., 2008. Model simulations of tidal changes in a coastal lagoon, the Ria de Aveiro. *Continental Shelf Research,* **28**, 1010-1025.

Aubrey, D.G., Speer, P.E., 1985. A Study of Non-Linear Tidal Propagation in Shallow Inlet/Estuarine Systems. Part I: Observations. Estuarine, *Coastal and Shelf Science*, **21**, 185-205.

Baldaque da Silva, A., 1893. Estudo histórico-hidrográfico sobre a barra e o porto de Lisboa. Imprensa Nacional.

Barnes, R.S.K., 1980. *Coastal lagoons*. Cambridge: Cambridge University Press. 106 pp.

Bernardes, B., 2007. *Hydrodynamical and Ecological Modelling of the North Sea*. MSc Thesis, Technical University of Lisbon, Lisbon, Portugal, pp. 81.

Bertness, M.D., Gough, L., Shumway, S.W., 1992. Salt tolerance and the distribuition of fugitive salt marsh plants. *Ecology*, **72**, 1832-1851.

Braunschweig, F., Martins, F., Chambel, P., Neves, R., 2003. A methodology to estimate renewal time scales in estuaries: the Tagus estuary case. *Ocean Dynamics*, **53**, 137–145.

Burling, M.C., Pattiaratchi, C.B., Ivey, G.N., 2003. The tidal regime of Shark Bay, Western Australia. *Estuarine, Coastal and Shelf Science*, **57**, 725 - 735.

Cabeçadas, G., Brogueira, M.J., Cabeçadas, L., 2000. *Southern Portugal: the Tagus and Sado estuaries*. In: Sheppard, C.R.C. (Ed.), Seas at the Millennium: an Environmental Evaluation. Elsevier Science Ltd, Oxford, UK, 151-165.

Caçador, I., Tiberio, S., Cabral, H.N., 2004. Species zonation in Corrioios salt marsh in the Tagus estuary (Portugal) and its dynamics in the past fifty years. *Hydrobiologia*, **587**, 205 – 211.

Caçador, I., Caetano, M., Duarte, B., Vale, C., 2009. Stock and losses of trace metals from salt marsh plants. *Marine Environmental Research*, **67** (2), 75-82.

Cahoon, D., Reed, D.J., Day, J.W., 1995. Estimating Shallow Subsidence in Microtidal Salt Marshes in Southeastern United States: Kaye and Barghoorn Revisited. *Marine Geology*, 128, 1–9.

Canário, J., Vale, C., Caetano, M., 2005. Distribution of monomethylmercury and mercury in surface sediments of the Tagus Estuary (Portugal). *Marine Pollution Bulletin*, **50**, 1121-1145.

Canário, J., Vale, C., Poissant, L., Nogueira, M., Pilote, M., Branco, V., 2010. Mercury in sediments and vegetation in a moderately contaminated salt marsh (Tagus Estuary, Portugal). *Journal of Environmental Sciences*, **22** (8), 1151 -1157.

Castaing, P., Allen, G. P., 1981. Mechanisms controlling seaward escape of suspended sediment from the Gironde: a macrotidal estuary in France. *Marine Geology*, **40**, 101–118.

Chao, B.F., Farr, T., LaBrecque, J., Binschadler, R., Douglas, B., Rignot, E., Shum, C.K., Wahr, J., 2002. Understanding sea level changes. In: Proceedings of IEEE IGARSS and the 24th Canadian Symposium on Remote Sensing. Toronto, Canada.

Church, J.A., White, N.J., 2006. A 20th century acceleration in global sea-level rise. *Geophysical Research Letters*, **33**, L01602.

Coelho, H., Neves, R., White, M., Leitão, P., Santos, A., 2002. A Model for Ocean Circulation on the Iberian Coast. *Journal of Marine Systems*, **32** (1-3), 153-179.

Costa, M.J., 1986. The Tagus Estuary as a Nursery. In: Estuarine processes: an application to the Tagus Estuary. Direcção-Geral da Qualidade do Ambiente, Lisbon, Portugal, 395–412.

Davidson-Arnott, R.G.D., Proosdij, D., Ollerhead, J., Schostak, L., 2002. Hydrodynamics and sedimentation in salt marshes: examples from a macrotidal marsh, Bay of Fundy. *Geomorphology*, **48**, 209-231.

Dias, J.M., 1993. *Comparação dos resultados de um modelo numérico bi-dimensional com observações de corrente no estuário do Tejo*. MSc Thesis, University of Lisbon, Portugal, 244 pp.

Dias, J.M., 2001. *Contribution to the study of Ria de Aveiro hydrodynamics*. PhD Thesis, Physical Department, University of Aveiro, Portugal, 288 pp.

Dias, J.M., Fernandes, E.H., 2006. Tidal and Subtidal Propagation in Two Atlantic Estuaries: Patos Lagoon (Brazil) and Ria de Aveiro Lagoon (Portugal). *Journal of Coastal Research*, **39**, 1423-1427.

Dias, J.M., Lopes, J.F., 2006. Implementation and Assessment of Hydrodynamic, Salt and Heat Transport Models: The Case of Ria de Aveiro Lagoon (Portugal). *Environmental Modelling & Software*, **21**, 1-15.

Dias, J.M., Sousa M., 2009. Numerical modeling of Ria Formosa tidal dynamics. *Journal of Coastal Research*, **56**, 1345-1349.

Dias, J.M., Valentim, J., 2011. Numerical modeling of Tagus estuary tidal dynamics. *Journal of Coastal Research*, **64**, 1495-1499.

Dias, J.M., Lopes, J.F., Dekeyser, I., 1999. Hydrological characterisation of Ria de Aveiro, Portugal, in early summer. *Oceanologica Acta*, **22** (5), 473–485.

Dias, J.M., Lopes, J.F., Dekesyser, I., 2000. Tidal characterization of Ria de Aveiro Lagon, Portugal. *Physics and Chemistry of the Earth*, **25**, 369-374.

Dias, J.M., Lopes J.F., Dekeyser I., 2001. Lagrangian Transport of Particles in Ria de Aveiro Lagoon, Portugal. *Physics and Chemistry of the Earth*, **26**(9), 721-727.

Dias, J.M., Lopes J.F., Dekeyser I., 2003. A Numerical Model System Application to the Study of the Transport Properties in Ria de Aveiro Lagoon. *Ocean Dynamics*, **3**, 53, 220-231.

Duarte, B., Caetano, M., Almeida, P.R., Vale, C., Caçador, I., 2010. Accumulation and biological cycling of heavy metal in four salt marsh species, from Tagus estuary (Portugal). *Environmental Pollution*, **158**, 1661–1668.

Dworak, J.A., Gómez-Valdés, J., 2002. Tide-induced residual current in a coastal lagoon of the Gulf of California. *Estuarine, Coastal and Shelf Science*, **57**, 99-109.

Fernandes, R., Silva, J., Leitão, P., Braunschweig, F., Neves, R., Domingos, J., 2004. Sistema de Monitorização Operacional para o Estuário do Tejo. In: APRH (Ed.), Proceedings do 7º Congresso da Água.

Fiadeiro, P., 1987. Estudos sobre a dinâmica e a qualidade da água no Estuário do Tejo. In: Anais do Instituto Hidrográfico. No. 8. Instituto Hidrográfico, 73–83.

Fortunato, A.B., Oliveira, A., 2005. Space and time variability of uncertainly in morphodynamic simulations. *Coastal Engineering*, **56** (8), 886-894.

Fortunato, A.B., Baptista, A.M., Luettich Jr., R.A., 1997. A three-dimensional model of tidal currents in the mouth of the Tagus estuary. *Continental Shelf Research*, **17**, 1689-1714.

Fortunato, A.B., Oliveira, A., Baptista, A.M., 1999. On the effect of tidal flats on the hydrodynarics of the Tams estuary. *Oceanologica Acta*, **22** (1), 31-44.

Fox, L., Valiela, I., Kinney, E. L., 2012. Vegetation Cover and Elevation in Long-Term Experimental Nutrient-Enrichment Plots in Great Sippewissett Salt Marsh, Cape Cod, Massachusetts: Implications for Eutrophication and Sea Level rise. *Estuaries and Coasts*, **35**, 445-458.

Freire, P., Taborda, R., Andrade, C., 2006. Caracterização das praias estuarinas do Tejo. In: APRH (Ed.), Proceedings do 8º Congresso da Água. Figueira da Foz.

Friedrichs, C.T., Aubrey, D.G., 1994. Tidal Propagation in Strongly Convergent Channels. Ocean Sciences Meeting.

Friedrichs, C.T., Perry, J.E., 2001. Tidal Saltmarsh Morphodynamics: A Synthesis. *Journal of Coastal Research*, **27**, 7–37.

Gameiro, C., Cartaxana, P., Brotas, V., 2007. Environmental drivers of phytoplankton distribution and composition in Tagus Estuary, Portugal. *Estuarine, Coastal and Shelf Science*, **75**, 21-34.

Geophysics Study Commitee, 1997. Overview and Recommendations. Estuaries, Geophysics and the Environment. Tech. rep., National Academy of Sciences, Washington, D. C., 1-10.

Guo, H., Pennings, S.C., 2012. Mechanisms mediating plant distributions across estuarine landscapes in a low-latitude tidal estuary. *Ecology*, **93**, 90-100.

Ibañez, C., Curco, A., Day Jr., J.W., Prat, N., 2000. Structure and productivity of microtidal Mediterranean coastal marshes. In: Weinstein, M.P., Kreeger, D.A. (Eds.), Concepts and Controversies in Tidal Marsh Ecology. Kluwer Academic Publishers, London, 875 pp.

Ketchum, B. H., 1950. Hydrographic Factors Involved in the Dispersion of Pollutants Introduced into Tidal Waters. *J. Boston Soc. Civ. Engrs*., **37**, 296 – 314.

Kolker, A., Engle, M.A., Orem, W.H., Bunnell, J.E., Lerch, H. E., Krabbenhoft, D.P., Olson, M.L., DeWild, J.F., Mc-Cord, J.D., 2008. Mercury, trace elements, and organic constituents in atmospheric fine particulate matter, Shenandoah National Park, Virginia, USA: A combined approach to sampling and analysis. *Geostandards and Geoanalytical Research*, **32**, 279–293.

Lefeuvre, J.C., Laffaille, P., Feunteun, E., Bouchard, V., Radureau, A., 2003. Biodiversity in salt marshes: from patrimonial value to ecosystem functioning. The case study of the Mont-Saint-Michel bay. *Comptes Rendus Biologies*, **326**, 125–131.

Leitão, P., Coelho, H., Santos, A., Neves, R., 2005. Modelling the main features of the Algarve coastal circulation during July 2004: A downscaling approach. *Journal of Atmospheric and Ocean Science*, **10** (4), 421–462.

Lillebø, A.I., Válega M., Otero M., Pardal M., Eduarda P., Duarte A.C., 2010. Daily and inter-tidal variations of Fe, Mn and Hg in the water column of a contaminated salt marsh: halophytes effect. *Estuarine Coastal and Shelf Science*, **88**, 91-98.

Lopes, J.F., Dias J.M., 2007. Residual circulation and sediments transport in Ria de Aveiro lagoon, Portugal. *Journal of Marine Systems*, **68**, 3-4, 507-528.

Lopes, J.F., Dias J.M., 2011. Circulação residual, transporte lagrangiano e distribuição de sedimentos na Ria de Aveiro. Jornadas da Ria de Aveiro 2011. 2-4/05/2011, Aveiro, Portugal.

Lopes, J.F., Dias, J.M., Dekeyser, I. 2006. Numerical modelling of cohesive sediments transport in the Ria de Aveiro lagoo, Portugal. *Journal of Hydrology*, **319**, 176-198.

Lopes, J.F., Almeida M.A., Cunha M.A., 2010. Modelling the ecological patterns of a temperate lagoon in a very wet spring season. *Ecological Modelling*, **221**, 2302-2322.

Lopes, C.L., Silva, P.A., Dias, J.M., Rocha A., Picado A., Plecha S., Fortunato A.B., 2011a. Local sea level change scenarios for the end of the 21st century and potential physical impacts in the lower Ria de Aveiro (Portugal). *Continental Shelf Research*, **31**, 1515-1526.

Lopes, C.L., Silva P.A., Rocha, A., Dias, J.M., 2011b. Sensitivity analysis of Ria de Aveiro hydro-morphodynamics to the sea level rise integration period. *Journal of Coastal Research*, **64**, 230-234.

Malhadas, M.S., Silva, A, Leitão P.C., Neves, R, 2009. Effect of the Bathymetric Changes on the Hydrodynamic and Residence Time in Óbidos Lagoon (Portugal). *Journal of Coastal Research*, **56**, 549 - 553.

Marques, B., Lillebø A.I., Pereira E., Duarte A.C., 2011. Mercury cycling and sequestration in salt marshes sediments: an ecosystem service provided by *Juncus maritimus* and *Scirpus maritimus*. *Environmental Pollution*, **159**, 1869-1876.

Martins, M., Calvão, T., Figueiredo, H., 1983. Estudo ambiental do estuário do Tagus, Estudo de Qualidade de Água. Resultados Referentes a observações sinópticas em 1982, CAN/Tagus 30-REL 27, Ministério da Qualidade de Vida, Lisboa, Portugal.

Martins, F., Neves, R., Leitão, P., 1998. A three-dimensional hydrodynamic model with generic vertical coordinate. In: Proceedings of Hydroinformatics'98. Vol. 2. Babovic, V. and Larsen, L. (Eds.), Balkema, Rotterdam, 1403–1410.

Martins, F., Leitão, P., Silva, A., Neves, R., 2001. 3D modelling in the Sado estuary using a new generic vertical discretization approach. *Oceanologica Acta*, **24**, 1–12.

Mcluscky, D.S., Elliott, M., 2004. *The estuarine ecosystem: ecology, threats, and management*. Oxford: Oxford University Press, 214 pp.

Meehl, G., Stocker, T.F., Collins, W.D., Friedlingstein, P., Gaye, A.T., Gregory, J.M., Kitoh, A., Knutti, R., Murphy, J.M., Noda, A., Raper, S.C.B., Watterson, I.G., Weaver, A.J., Zhao, Z.-C., 2007. Global climate projections. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Mille, H.L. (Eds.), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I* *to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK and New York, USA, 747–846.

Miranda, L.B., Castro, B.M., Kjerfve, B., 2002. *Princípios de Oceanografia Física de Estuários*. Edusp - Editora da Universidade de São Paulo, 424 pp.

Mitsch, W.J., Gosselink, J.G., 2000. The value of wetlands: importance of scale and landscape setting. Ecological economics. *The Values of Wetlands: Landscapes and Institutional Perspectives*, **35** (1), 25–33 (Special issue).

Montero, P., 1999. *Estudio de la Hidrodinámica de la Ría de Vigo Mediante un Modelo de Volúmenes Finitos*. Ph.D. Thesis, Universidad de Santiago de Compostela, Spain, 174 pp.

Moreira, M.H., Queiroga, H., Machado, M.M., Cunha M.R., 1993. Environmental gradients in a southern estuarine system: Ria de Aveiro, Portugal, implication for a soft bottom macrofauna colonization. *Netherlands Journal of Aquatic Ecology*, **27**, 465-482.

Morgado, F., Queiroga, H., Melo, F., Sorbe, J. C., 2003. Zooplankton abundance in a coastal station of the Ria de Aveiro inlet (north-western Portugal): relations with tidal and day/night cycles. *Acta OEcologica*, **24**, 175–181.

Neves, F.J., 2010. *Dynamics and hydrology of the Tagus estuary: results from in situ observations*. PhD Thesis, University of Lisbon, Portugal, 210 pp.

Oliveira, I.B.M., 1993. Port of Lisbon – Improvement of the Access Conditions Through the Tagus Estuary Entrance. In: Proceedings of the 23rd International Conference of Coastal Engineering. 2745–2757.

Pawlowicz, R., Beardsley, B., Lentz, S., 2002. Classical tidal harmonic analysis including error estimates in MATLAB using T_TIDE. *Computers & Geosciences*, **28**, 929-937.

Pedro, S., Canastreiro, V., Caçador, I., Pereira, E., Duarte, A.C., Almeida, P.R., 2008. Granulometric selectivity in Liza ramado and potential contamination resulting from heavy metal load in feeding areas. *Estuarine, Coastal and Shelf Science*, **80**, 281 -288.

Pennings, S.C., M.D. Bertness, 2001. *Salt marsh communities*. In: Marine community ecology. Bertness, M.D., Gaines, S.D. and M.E. Hay (editors). Sinauer Associates, Sunderland, Massachusetts, USA. 550 pp.

Pereira, C., Salvador S., Arrojado C., Silva Y.J., Santos A.L., Cunha A., Gomes N.C.M., Almeida A., 2011. Evaluating seasonal dynamics of bacterial communities in marine fish aquaculture: a preliminary study before applying phage therapy. *Journal of Environmental Monitoring*, **13** (4), 1053 – 1058.

Picado, A., 2008. *Degradation of the salt pans in Ria de Aveiro: An Hydrodynamical Study*. MSc Thesis, Physical Department, University of Aveiro, 50 pp.

Picado, A., Dias J.M., Fortunato A., 2010. Tidal changes in estuarine systems induced by local geomorphologic modifications. *Continental Shelf Research*, **30** (17), 1854-1864.

Pires, A., Quintino V., Gentil F., Freitas R., Rodrigues A.M., 2012 (in press). Reproductive biology of a brooding Diopatra species: *Diopatra marocensis*. *Estuarine, Coastal and Shelf Science*.

Portela, L., Neves, R., 1994. Numerical modelling of suspended sediment transport in tidal estuaries: a comparison between the Tagus (Portugal) and the Scheldt (Belgium- The Netherlands). *Netherlands Journal of Aquatic Ecology*, **28**, 329–335.

Prandle, D., 1982. The vertical structure of tidal currents and other oscillatory flows. *Continental Shelf Research*, **2**, 191–207.

Pritchard, D.W., 1967. Estuarine hydrography. *Advances in Geophysics*, **1**, 243-280.

Pugh, D., 2004. *Changing Sea Levels - Effects of Tides, Weather and Climate*. Cambridge University Press, Cambridge, 265 pp.

Rahmstorf, S., 2007. A semi-empirical approach to projecting future sea-level rise. *Science*, **315**, 368–370.

Reboreda, R., Caçador, I., 2007. Copper, zinc and lead speciation in salt marsh sediments colonised by *Halimione portulacoides* and *Spartina maritima*. *Chemosphere*, **69**, 1655–1661.

Reed, D.J., Spercer, T., Murray, A.L., French, J.R., Leonard, L., 1999. Marsh surface sediment deposition and the role of tidal creeks: implications for created and managed coastal marshes. *Journal of Coastal Conservation*, **5**, 81-90.

Rodrigues, D.A., Teles, M., Leendertse, J.J., 1986. Numerical modelling of the Tejo estuary for currents and water quality predictions. In: Estuarine processes: an application to the Tagus Estuary. Direcção-Geral da Qualidade do Ambiente, Lisbon, Portugal, 7-22.

Rodrigues da Silva, M.C., 2003. *Instrumentos de Apoio à Gestão de Estuários. Indicadores Ambientais*. PhD. Thesis, Universidade Nova de Lisboa, Faculdade de Ciências e Tecnologia.

Santos, M., Neves, R., Leitão, P., Pereira, P., Pablo, H., Fernandes, L.D., Carvalho, S.M., Alves, C.P., 2006. Qualidade da água da Lagoa de Óbidos: Que futuro? XII Encontro Nacional de Saneamento Básico, Cascais 2006.

Saraiva, S., Pina, P., Martins, F., Santos, M., Braunschweig, F., Neves, R., 2007. Modelling the influence of nutrient loads on Portuguese estuaries. *Hydrobiologia*, **587**, 5–18.

Silva, A., 1996. Implementação de um Modelo Hidromorfológico para a Barra do Douro Contribuição para a Compreensão do Sistema. 3º Congresso da Água, Lisboa.

Silva, J.F., Duck, R.W., 2001. Historical changes of bottom topography and tidal amplitude in the Ria de Aveiro, Portugal—trends for future evolution. *Climate Research*, **18**, 17-24.

Silva, A.J.R., Leitão, P.C., Leitão, J.C., Braunschweig, F., Neves, R., 2002. Ria Formosa 3D hydrodynamic model. A contribution for the understanding of the Faro Olhão inlet processes. Litoral 2002, The Changing Coast. EUROCOAST, Portugal, 197–207.

Silva, H., Caldeira, G., Freitas, H., 2007. Population dynamics and tolerance to salinity in *Salicornia ramosissima*. *Ecological Research*, **22**, 125-134.

Silva, H., Dias, J.M., Caçador, I., 2009. Is the salt marsh vegetation a determining factor in the sedimentation processes? *Hydrobiologia*, **621**, 33-47.

Simas, T.C., Ferreira, J.G., 2007. Nutrient enrichment and the role of salt marshes in the Tagus estuary (Portugal). *Estuarine, Coastal and Shelf Science*, **75**, 393-407.

Simas, T.C., Nunes, J. P., Ferreira, J. G., 2001. Effects of global climate change on coastal salt marshes. *Ecological Modelling*, **139**, 1–15.

Sivakholundu, K.M., Kathiroli, S., Mani, J.S., Idichandy, V.G., 2006. Evaluation of River Regulatory Measures in Hughly Estuary using Tidal Asymmetry Characteristics. IEEE.

Sousa, M.C., Dias, J.M., 2007. Hydrodynamic model calibration for a mesotidal lagoon: the case of Ria de Aveiro (Portugal). *Journal of Coastal Research*, **50**, 1075-1080.

Sousa, A.I., Caçador, I., Lilebø, A.I., Pardal, M.A., 2008a. Heavy metal accumulation in *Halimione portulacoides*: Intra- and extra-cellular metal binding sites. *Chemosphere*, **70**, 850-857.

Sousa, A.I., Lilebø, A.I., Caçador, I. Pardal, M.A., 2008b. Contribution of *Spartina maritima* to the reduction of eutrophication in estuarine systems. *Environmental Pollution*, **156**, 628–635.

Sousa, A.I., Lillebø, A.I., Pardal, M.A., Caçador, I., 2010a. Productivity and nutrient cycling in salt marshes: Contribution to ecosystem health. *Estuarine, Coastal and Shelf Science*, **87**, 640-646.

Sousa, A.I., Lillebø, A.I., Pardal, M.A., Caçador, I., 2010b. The influence of *Spartina maritima* on carbon retention capacity in salt marshes from warm-temperate estuaries. *Marine Pollution Bulletin*, **61**, 215-223.

Sousa, A.I., Lillebø A.I., Pardal M.A., Caçador I., 2011. Influence of multiple stressors on the auto-remediation processes occurring in salt marshes. *Marine Pollution Bulletin*, **62**, 7, 1584–1587.

Suchrow, S., Jensen, K., 2010. Plant species responses to an elevational gradient in German North Sea salt marshes. *Wetlands*, 30, 735-746.

Sumares, D.M.S., 2007. *Local perceptions and postures towards the SPA "Ria de Aveiro"*. MSc Thesis, University of Aveiro, 160 pp.

Taboada, J.J., Prego, R., Ruiz-Villarreal, M., Montero, P., Gómez-Gesteira, M., Santos, A., Pérez Villar, V., 1998. Evaluation of the seasonal variation in the residual patterns in the Ría de Vigo (NW Spain) by means of a 3D baroclinic model. *Estuarine, Coastal and Shelf Science*, **47**, 661–670.

Trancoso, A.R., Saraiva, S., Fernandes, L., 2005. Modelling macroalgae using a 3D hydrodynamic-ecological model in a shallow, temperate estuary. *Ecological Modelling*, **187**, 232-246.

Townend, I., Fletcher, C., Knappen M., Rossington, K., 2011. A review of salt marsh dynamics. *Water and Envirnonment Journa*l, **25**, 477-488.

Vale, C., Sundby, B., 1987. Suspended Sediment Fluctuations in the Tagus Estuary on Semi-Diurnal and Fortnightly Time-Scales. *Estuarine, Coastal and Shelf Science*, **25** (5), 495–508.

Válega, M., 2009. *Mobilidade, acumulação e transformação do mercúrio em sapais*. PhD Thesis, Chemistry Department, University of Aveiro, 162 pp.

Válega, M., Lillebø, A.I., Caçador, I., Pereira, M.E., Duarte, A.C., Pardal, M.A., 2008. Mercury mobility in a salt marsh colonised by *Halimione portulacoides*. *Chemosphere*, **72**, 1607-1613.

Valente, A., Silva, J., 2009. On the observability of the fortnightly cycle of the Tagus estuary turbid plume using MODIS ocean colour images. *Journal of Marine Systems*, **75**, 131–137.

Valiela, I., Teal, J.M., 1974. *Nutrient limitation in salt marsh vegetation. Ecology and halophytes*. Reimold of W.H. Queen, 547-563. New York: Academic Press.

Van Proosdij, D., Davidson-Arnott, R.G.D., Ollerhead, J., 2006. Controls on spatial patterns of sediment deposition across a macro-tidal salt marsh surface over single tidal cycles. *Estuarine Coastal and Shelf Science*, **69**, 64-86.

Vaz, N., 2007. *Study of heat and salt transport processes in the Espinheiro Channel (Ria de Aveiro)*. PhD Thesis, Physical Department, University of Aveiro, Portugal, 151 pp.

Vaz, N., Dias, J.M., 2011. Cross-sectional and stratification patterns induced by tidal and river discharge changes in a tidal channel: a modelling study. *Journal of Coastal Research*, **64**, 1614-1618.

Vaz, N., Dias, J.M., Leitão, P.C., Martins, I., 2005. Horizontal patterns of water temperature and salinity in an estuarine tidal channel: Ria de Aveiro. *Ocean Dynamics*, **55**, 416–429.

Vaz, N., Dias, J.M., Leitão, P.C., Nolasco, R., 2007. Applicationt of the Mohid-2D model to a mesotidal temperate coastal lagoon. *Computers & Geosciences*, **33**, 1204-1209.

Vaz, N., Dias J.M., Leitão P.C., 2009a. Three-dimensional modelling of a tidal channel: the Espinheiro Channel (Portugal). *Continental Shelf Research*, **29**, 29-41.

Vaz, N., Fernandes L., Leitão P.C., Dias J.M., Neves R., 2009b. The Tagus estuarine plume induced by wind and river runoff: Winter 2007 case study. *Journal of Coastal Research*, **56**, 1090-1094.

Vaz, N., Mateus M., Dias, J.M., 2011. Semidiurnal and spring-neap variations in the Tagus Estuary: Application of a process-oriented hydro-biogeochemical model. *Journal of Coastal Research*, **64**, 1619-1623.

Vernberg, F.J., 1993. Salt-marsh processes: A Review. *Environmental Toxicology and Chemistry*, **12** (12), 2167–2195.

Villarreal, M.R., Montero, P., Taboada, J.J., Prego, R., Leitão, P.C., Péres-Villar, V., 2002. Hydrodynamic model study of the Ria de Pontevedra under estuarine conditions. *Estuarine, Coastal and Shelf Science*, **54** (1), 101–113.

Villarreal, M.R., Coelho, H., Díaz del Río, G., Nogueira, J., 2004. Slope current in the Cantabrian: observations and modeling of seasonal variability and interaction with Aviles Canyon. 1st EGU General Assembly, France.