Chapter

Numerical Modeling Tools Applied to Estuarine and Coastal Hydrodynamics: A User Perspective

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Abstract

Estuarine and coastal areas have been intensively studied given their complexity, ecological, and societal value and the importance of their ecosystem services. Estuarine and coastal management must be based on a sound characterization of these areas, which is achievable complementing the comprehensive field measurements with numerical models solutions. Based on a detailed comparison between two close-by, but extremely different, Portuguese estuaries (the Douro and Minho estuaries), this chapter intends to discuss how accurately numerical modeling tools can provide relevant information for a variety of coastal zones. They can be very useful for various applications in the planning and management fields, such as coastal and infrastructures protection, harbor activities, fisheries, tourism, and coastal population safety, thus supporting an effective and integrated estuarine and coastal management, which must consider both the safety of the populations and the sustainability of the marine ecosystems and services. In particular, the capacity of the numerical models to give a detailed characterization of morpho-hydrodynamic processes, as well as assess and predict the effects of anthropogenic interventions, extreme events and climate change effects, are presented.

Keywords: estuaries and coasts, hydrodynamics, field measurements, numerical modeling, coastal zones management

1. Introduction

The Coastal Zone is strategically important from environmental, economic, and societal points-of-view. Coastal zones are densely populated, concentrating human settlements, leisure activities, fisheries, and other marine industries. In the last decades, the population, economic assets, and urbanizations in the coastal zones have experienced a rapid growth, and a continuous increase of population in these regions is expected for the near future [1, 2]. The intensification of anthropic activities in coastal regions can boost their vulnerability to extreme events and, consequently, augment damages, cause injuries, and even loss of lives. In the present context of climate changes, an increase in the frequency and strength of extreme events have been reported [2], with potentially severe consequences for both society and environment, affecting human health and infrastructures, and resulting in the loss of property and habitats [3, 4]. For example, a loss of 70% of the coastal wetlands by 2080 is predicted due to a combination of sea-level rise, intensification of coastal urbanization, and increase of constructions for flood defense [5, 6]. Wetlands are highly productive areas, essential not only for fisheries and nature conservation, but also as a natural protection against floods. Their loss can have high socio-economic costs. Thus, extreme events, climate change conditions, and anthropogenic activities can put at risk the Coastal Zone's prolific flora and fauna and the ecosystem services they provide (e.g., food, fisheries, tourism, cultural services, energy, water abstraction, raw materials, water desalination/treatment, climate, and natural hazard regulation).

In this context, there is a need for scientific and technical information available to decision-makers, to support a sustainable coastal management, and avoid serious damages and higher losses for the littoral populations and coastal environments [7, 8]. This information is crucial to implement early warning systems and find solutions to reduce the negative impacts associated with extreme events (floods, droughts, storm surges, and coastal storms), climate change, and man-made interventions in the Coastal Zone. These can help to reduce exposure and vulnerability, mitigate the associated risks and promote the adaptation and the resilience of the communities to the potential adverse impacts, even though risks cannot be fully mitigated.

Effective protection of the Coastal Zone requires a comprehensive understanding of its morpho-hydrodynamic processes, as well as of the effects of these processes on the territory and the ecosystems. Coasts are land-ocean transition areas and, therefore, Coastal Zone assessment must consider land-ocean interactions, including estuaries and marine areas [9]. Meteorological, oceanographic, morphological, chemical, and biological parameters, obtained through *in-situ* measurement campaigns, are key descriptors to represent and understand the present state and the main evolution trends of the estuarine and coastal systems. However, field campaigns are usually expensive, often difficult and not always effective. As a consequence, there is a lack of continuous and long-term observations, being these regions generally under-sampled and poorly understood [10]. This limited knowledge, related with the lack of systematic monitoring and interface system complexity, leads to a high degree of uncertainty about the expectable effects of future scenarios associated with man-made interventions, climate change, and extreme events.

A complete estuarine/coastal dynamics characterization and, particularly, the assessment of future conditions, could be achieved through results obtained with numerical models [7, 11]. These models provide predictions of future trends and outcomes for different scenarios, hence supporting the implementation of sustainable action plans. Nevertheless, it should be noticed that field data is crucial for proper implementation of numerical models. Measured data are needed to define the models' initial states, forcing conditions, and static computation of calibration parameters values, or its dynamic computation using data assimilation techniques. Field data are also required to assess the numerical models performance comparing model results to measurements. So, despite the fact that advanced numerical models are excellent tools to understand the Coastal Zone behavior, comprehensive periodic or continuous monitoring campaigns in estuarine and coastal regions are still crucial to ensure the effectiveness of model application. Moreover, some of the complex morpho-hydrodynamic processes that take place in the coastal environment are still poorly understood. The combination of numerical and field monitoring methodologies should be pursued to improve our knowledge about those processes.

2. Numerical models and the *ensembles* technique

Considerable effort has been made to provide the most accurate estimations for the complex estuarine/coastal circulation, using either simple box models or complex numerical model suites. With the development of high-resolution numerical modeling systems, essential decision-making support instruments became available for an effective and integrated marine and coastal management. Numerical models are essential to properly assess the effect of each forcing driver, accurately representing the dynamical processes of estuarine/coastal systems [10]. Their input can be manipulated to represent the impact of changes in initial and boundary conditions, topo-bathymetric features, and coastal structures [12]. They can help to overcome the lack of field observations and measurements, allowing a full characterization of the morpho-hydrodynamic, chemical, and biological behavior of coastal regions, and providing valuable information to promote population, services and ecosystems safety [13, 14].

The current modeling tools available for coastal and estuarine studies allow an almost complete representation of the physical conditions of these areas. There is a large variety of models and techniques. The numerical techniques can be based on several methods, such as finite element, finite difference, finite volume, boundary element, or Eulerian-Lagrangian. The time integration algorithms can be explicit, implicit, semi-implicit, or characteristic-based. The functions can be of the first, second, or higher order, and the spatial dimensions can be one-dimensional (either in the horizontal plane 1DH or in the vertical 1DV), two-dimensional depth integrated (2DH) or lateral integrated (2DV), or three-dimensional (3D) [15, 16]. It is therefore important to properly select the adequate numerical model tool for the specific problem(s) the user wants to solve. This selection should be made in each case considering a compromise between the available data for model calibration and validation, the objectives of the model simulations and the available computational resources.

The most powerful modeling suites currently available (Delft3D, open TELEMAC-MASCARET, SWASH, ROMS, MOHID, SELFE, ADCIRC, Tuflow-FV, FVCOM, Mike21, etc.) are able to simulate several physical processes and environmental actions, such as flood/ebb cycles, bathymetry dynamics, friction, river discharge, water levels dynamics, currents velocity, wind action, waves, density effects, sediment transport, or Coriolis force, among others. Normally, numerical tools to model these processes are available in different and separate modules that the user can select depending on the desired complexity of the solutions. Modeling suites can also contain additional modules that allow the characterization of biological and ecological processes that are fundamental for water quality assessment, recurring to both Lagrangian and Eulerian transport approaches, including larvae migration, ecological status, nutrients concentration, pollutant evolution, etc. But, even these biogeochemical modules are completely dependent on the results obtained by the modules that represent the hydrodynamic patterns. The hydrodynamic conditions (water levels, currents velocities, temperature, and salinity) resulting, for example, from the complex interaction between tides, waves, storm surge, wave set-up, and river discharge, will define the main transportation patterns of sediments, larvae and pollutants with a direct effect on the ecosystems.

Most of the numerical models applied to coastal and estuarine regions can be implemented in 2DH/V or 3D configurations. 2DH simulations simplify the computational requirements by solving the shallow water equations. It has been demonstrated that this kind of models can accurately reproduce current velocity, flood extent, and water levels, being useful to complement risk assessment tools and early warning systems, because less computational resources are required and the numerical solutions are much faster obtained. Several authors used 2DH models with satisfactory results [14, 17–24], though 3D models are required to properly represent several processes, like vertical stratification, vertical current profiles, turbulent mixing processes, sediment transport, turbidity, water quality, effects of salinity, and temperature gradients on river plumes or salt-wedge estuarine configurations [25–28].

Regarding the equations and their approximations, 3D models are normally based on the Navier-Stokes equations or its depth-integrated version, the shallow water equations, which are applicable when the horizontal scale is much greater than the vertical scale. The shallow water equations applied to 1DH or 2DH problems are also known as Saint-Venant equations [29]. Despite their wide applicability, shallow water equations are not able to properly represent small relative amplitude waves propagating in shallow water conditions, which is of upmost importance to simulate the superposition between waves and currents, the effects of the waves on the sediment transport, the waves interaction with the bottom, or other wave processes, as shoaling, reflection, refraction, diffraction and decomposition [16, 30]. For this purpose, more sophisticated models are needed, like the ones of Boussinesq, Korteweg de Vries, Serre, or Green-Naghdi. These models include additional terms that take into account the nonhydrostatic effects of free surface curvature. Boussinesq equations [31, 32] are derived from the Navier-Stokes equations by depth-averaging them considering the pressure as nonhydrostatic [33]. Boussinesq-type equations can account nonlinear and dispersive effects considering various degrees of accuracy. The Korteweg de Vries equation, which was first introduced by Boussinesq and rediscovered by Korteweg and de Vries [32, 34] describes weakly nonlinear shallow water waves, allowing the representation of solitary wave solutions [35]. However, it must be considered that the wave dynamic becomes strongly nonlinear in the final stages of shoaling, particularly in the surf and swash zones. To properly represent this phenomenon and provide a correct description of the waves up to the breaking point, fully nonlinear equations should be considered, as the Serre or Green-Naghdi equations. Serre equations [36], also known as the Su-Gardner equations, are deduced from the fundamental equations of fluid mechanics, but taking into account the incompressibility of the fluid, the vertical uniformity of the velocity field and the conservation laws [16]. Finally, Green-Naghdi nonlinear equations [37] considers the 3D water-wave problem with a free surface and a variable bottom, and taking into account that the fluid can be rotational [38].

A comparison between the effectivity of different models and approximations is a really difficult task if the models are not implemented for the same region and considering the same initial/forcing conditions. Nevertheless, there are already some works where the capabilities of different numerical models are compared. Walstra et al. [39] applied the PISCES and the Delft3D models to coastal environments, depicting a general good overall agreement of both models, except for Delft3D under low wave conditions and for PISCES when a flow generated by the breaking of the waves on the shoal is presented. Rahman and Venugopal [25] compared 3D versions of open TELEMAC-MASCARET and Delft3D to represent the hydrodynamic conditions of the Pentland Firth and also the tidal regime energy in that area. Open TELEMAC-MASCARET seems to show the best consistency with the field data, although Delft3D also obtained good results for water level variations. The same models but in a 2DH version were selected by Iglesias et al. [14] to model floods at the Douro estuary. A small underestimation and overestimation of Delft3D and open TELEMAC-MASCARET, respectively, were observed for surface elevation for nonflood scenarios. For historical floods, the two models obtained very similar results, despite using different numerical approximations. The different numerical approximations of Mike 21 FM, Delft3D, and Delft3D FM were tested by Symonds et al. [24], confirming that despite the differences in the grids configuration, all the approaches accurately predict hydrodynamic conditions in complex estuarine regions. They also demonstrate that the unstructured models present a higher computational efficiency.

There is, hence, a wide range of numerical models that can be applied to estuarine/coastal zones to proper characterize these complex areas and gain a deep understanding of their hydrodynamic characteristics. Through the implementation of numerical algorithms, the circulation in these systems can be reproduced and different hydrodynamic processes can be represented. And knowledge about the hydrodynamic patterns influenced by bottom morphological changes may allow assessment and forecasting of the effects of hazardous and extreme events, anthropogenic intervention, or climate change. Hydrodynamic modeling has therefore been the focus of a large number of previous works in estuarine environments [11, 14, 17, 21, 22, 40–50].

Nowadays, the available powerful computational resources and complex numerical model suites allow the implementation of high-resolution studies with accurate results. Some examples are the works of Dias et al. [50] and Jones and Davies [46] for estuarine tides, Pinho and Vieira [44] for estuarine salt-water intrusion, Robins and Davies [21] and Sutherland et al. [43] for estuarine and coastal morpho-hydrodynamic behavior, Pinho et al. [45] and Iglesias et al. [14] for estuarine flood studies, Pinho et al. [51] for coastal waters hydrodynamics and water quality, Antunes do Carmo et al. [16] for agitation in harbors, Antunes do Carmo and Seabra-Santos [30] for coastal protection, and Monteiro et al. [22] for coastal circulation and river plumes. However, every modeling system has its own advantages and limitations, and model solutions will display uncertainties related with errors, calibration parameters, or model assumptions and forcing functions. Given the need for accurate forecasts, finding and implementing new solutions to avoid such errors is crucial. A single model can have biases, high variability, or inaccuracies related with the specification of initial conditions or the representation of physical processes in the models, causing large uncertainties in numerical prediction systems that can affect the reliability of the obtained results [52]. So, why not use several models to reduce uncertainties?

The e*nsembles* technique is based on the combination of several numerical models solutions and can improve the forecast results when compared to a single model-based approach, even if the number of members in the models *ensemble* is as few as two [53]. *Ensemble* is a French word that means "set," "cluster," or "together" and usually refers to a unit or group of complementary parts that contribute to a single effect [54]. *Ensemble* modeling is a method that consists of running two or more related numerical models with the same conditions and then synthesizing the results into a single solution. This single solution will improve the accuracy of the final forecast, compared to the solutions provided by each model. It has been demonstrated that combining models generally increases the skill, reliability, and consistency of model forecasts [55], and *ensemble* simulations are currently applied in atmospheric and climate sciences to predict meteorological behavior and climate change effects ([56, 57]; IPCC: https://www.ipcc.ch/), being also used in other sectors, such as public health [58], agriculture [59], and more recently, in estuarine hydrodynamics [14].

Two types of *ensembles* can be defined: single-model and multi-model *ensembles*. The single-model *ensemble* is based on a single model that is run several times with very slight differences in the initial and/or boundary conditions, producing different simulation results. The multi-model *ensemble*, as its name suggests, considers different numerical models that present different structural complexities. Each model is run using the same initial and boundary conditions. The multi-model *ensemble* clearly outperforms both single models and the single-model *ensemble* [60–62].

To combine the outputs of different models, several statistical techniques can be applied, considering the mean, the median, a linear regression, weighted average, or linear programming techniques, among others [52, 57, 63–65]. Computing the mean of the *ensemble* members' outputs is one of the most used methods; using the mean, the effect of combining models to reduce errors can be expressed in terms of bias and variance [54]. The bias is used to measure the extent to which the *ensemble* result, averaged over the *ensemble* members, differs from the target function. The variance can be defined as the extent to which the considered *ensemble* models disagree [66]. Being the root mean square error (RMSE), the sum of the model variance, and square of the bias, the model's *ensemble* suitability can be expressed in terms of the mean RMSE of the *ensemble* members [14].

The *ensembles* technique can thus be used to improve single models forecasts, reduce their uncertainty, and provide the most accurate results for a variety of sectors, as previously mentioned. This is the main objective of the *EsCo-Ensembles* project, a FCT (*Fundação para a Ciência e a Tecnologia*, Portugal) funded project that intends to use a numerical models *ensemble* to simulate estuarine hydrodynamic patterns in the face of anthropic interventions, extreme events, and climate changes. In this project, the *ensembles* technique will be applied to two of the main estuaries of the Portuguese coast: the Douro and Minho estuaries.

3. A Portuguese case study: Douro and Minho estuaries

The need for an accurate forecasting based on numerical models becomes clear when the Douro and Minho estuarine regions are analyzed. Although these estuaries, located in the western coast of the Iberian Peninsula, are separated by a distance of less than 100 km (**Figure 1**), their dynamics and environmental conditions are completely different (**Table 1**). Despite presenting similar seasonal river flow regimes (**Figure 2**), with minimum values in summer and maximum values in the rainy winter season, flow values and patterns differ. For the Minho river, between 1970 and 2018, a maximum daily mean river flow of 4600 m^3/s was measured at Frieira dam; whereas the Douro presented a maximum daily mean river flow of 10,990 m^3/s at Crestuma-Lever dam between 1986 and 2018. The difference between these two systems is also evident when river flood peak discharges associated with different return periods are estimated (**Table 2**). The different river discharge patterns suffice to support the need for a focused and local hydrodynamic characterization of the two estuaries when trying to avoid future risks related with human interventions (dredging, ports, alterations in the estuarine banks, designing of breakwaters, etc.), extreme events such as coastal and estuarine floods or storm surges, sea-level rise and the increase in the number and/or intensity of extreme events associated with climate change predictions. However, a comparison of the main estuaries characteristics and bathymetric conditions (**Table 1** and **Figures 1** and **3**), reinforces this necessity. For the river flood peak discharges analysis, we assumed that the probability distribution for extreme flow events follows a Gumbel law [67]. Daily mean river flow data was provided by the SNIRH-*Sistema Nacional de Informação de Recursos Hídricos* (https://snirh.apambiente.pt/), measured between 1986 and 2018 at the Crestuma-Lever dam, and by *Confederación Hidrográfica Miño-Sil* (https://www.chminosil.es/es/), measured between 1970 and 2018 at the

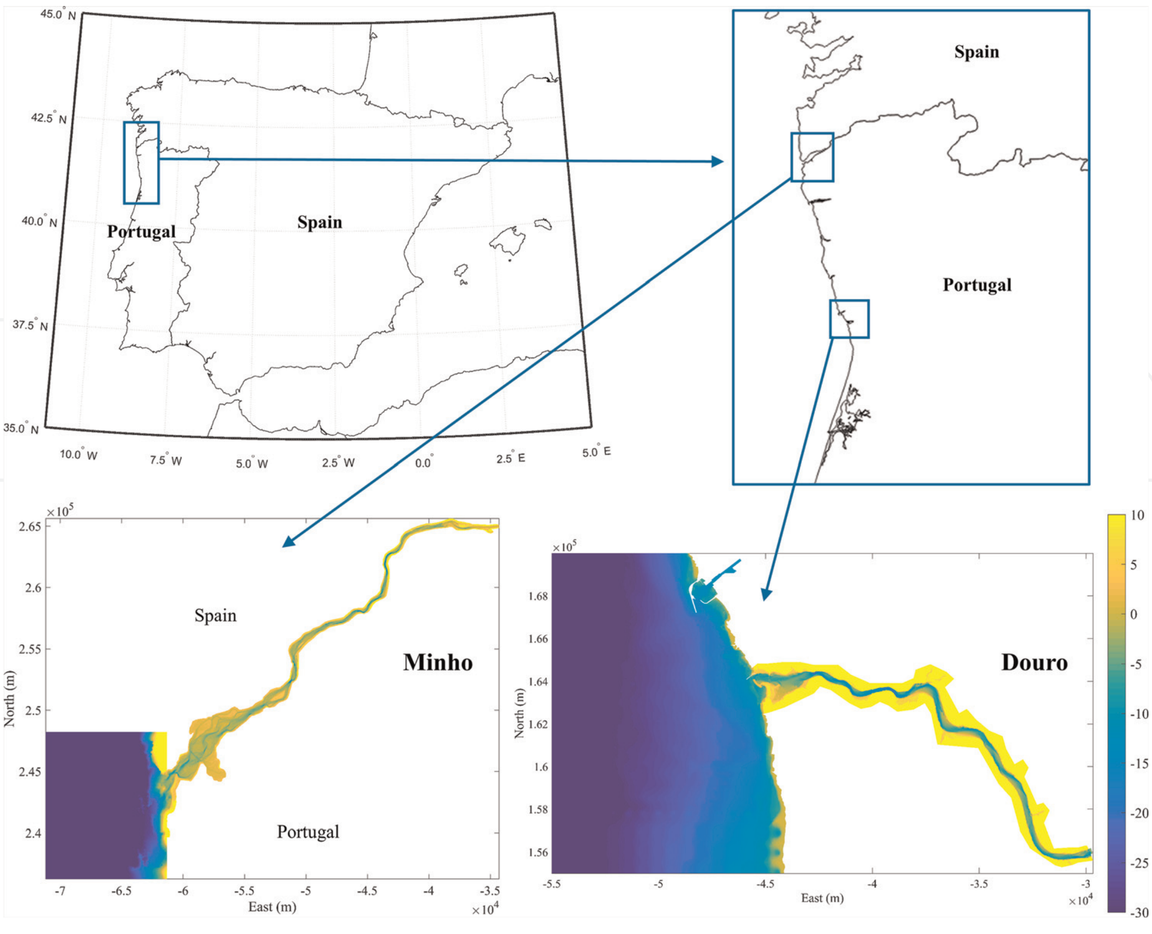

Figure 1.
Minho and Douro estuaries' location and bathymetry (in metres—vertical datum MSL-mean sea level). The horizontal coordinates of the bathymetric maps are in datum PT-TM06/ETRS89.

	Douro	Minho
Hydrographic basin (km^2)	97,603	17,080
River length (km)	927	300
Estuarine mouth	Artificial (breakwaters)	Natural (rocks)
Estuarine limit	Artificial (dam)	Natural (limit of tide penetration)
Estuarine extension (km)	21	35
Estuarine river flow	Artificial (dam)	Artificial (dam)
Mean depth (m)	−13.8	−7.6
Maximum estuarine width (m)	1,300	2,100
Minimum estuarine width (m)	135	160

Table 1.
Main characteristics of each considered estuary.

Frieira dam. It should be noted that the presented extreme values refer to average daily extremes, since annual instantaneous peak values were not available. Thus, higher flood peak extremes are expected for both estuaries.

The bathymetric map for the Minho estuary (**Figure 1**) was constructed using several topographic and bathymetric data sets: topographic data provided by the Portuguese Direção Geral do Território (DGT; http://www.dgterritorio.pt/) as a Digital Terrain Model (DTM) obtained from a nation-wide altimetric survey carried

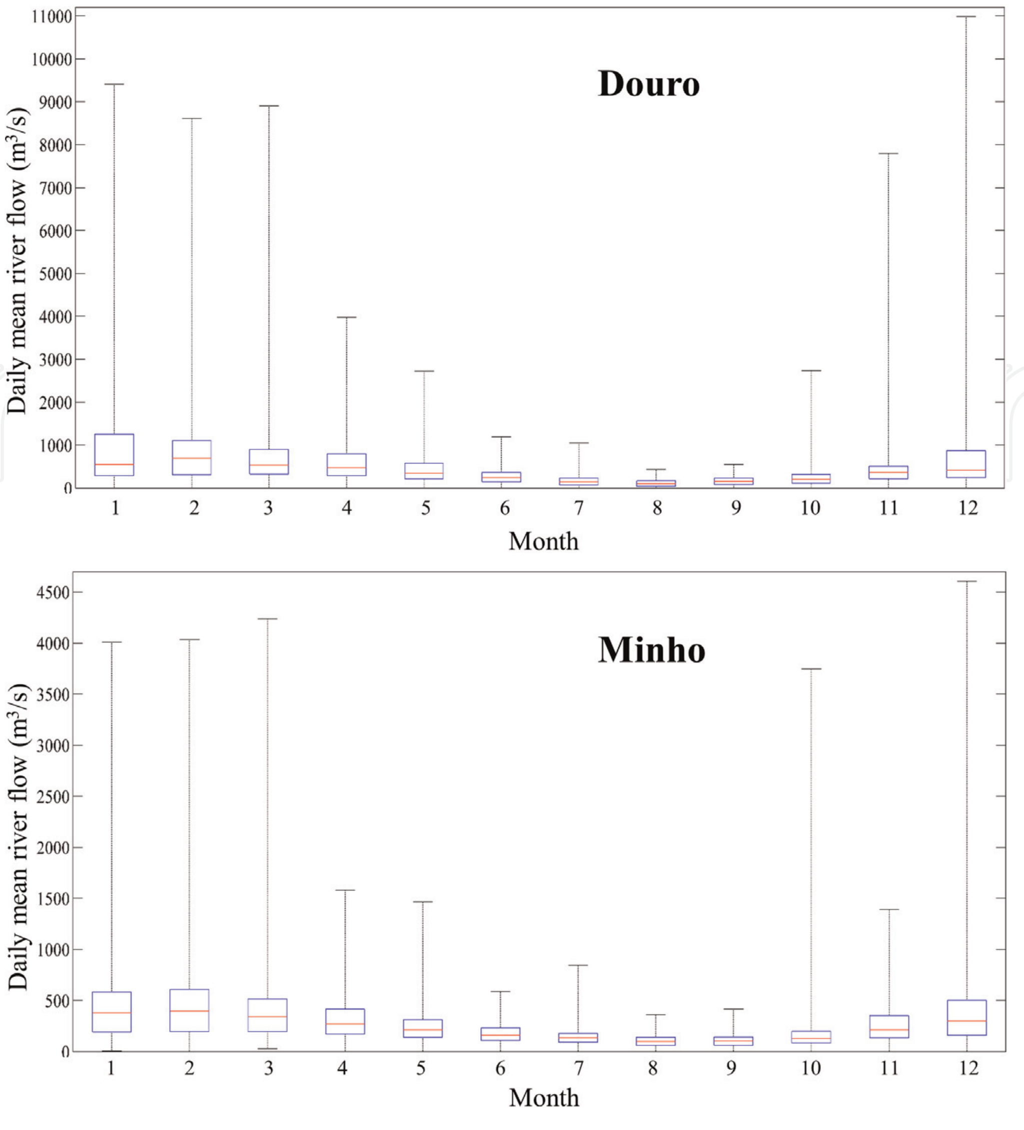

Figure 2.
Box plots representing the monthly minimum (lower whisker), lower quartile (25%, bottom box limit), median (red line), upper quartile (75%, top box limit), and maximum (upper whisker) daily mean river flow values of the Douro and Minho rivers flows, from 1986 to 2018 and from 1970 to 2018, respectively. Data source: SNIRH (https://snirh.apambiente.pt/) and Confederación Hidrográfica Miño-Sil (https://www.chminosil.es/es/).

T (years)	Q Douro (m^3/s)	Q Minho (m^3/s)
10	7,655	3,308
20	9,215	3,944
50	11,235	4,767
100	12,748	5,383
200	14,256	5,998
500	16,246	6,809
1000	17,749	7,421

Table 2.
River flood average daily extreme discharges (Q) associated with different return periods (T).

on in 2011 with a LiDAR (light detection and ranging); and bathymetric data provided by the Portuguese *Instituto Hidrográfico* (IH; http://www.hidrografico.pt/), obtained in 2006. The Douro bathymetry (**Figure 1**) was extracted from a 2009 bathymetric survey performed by the IH. The sand spit topography was taken from a 2015 topographical survey [68], and the adjacent coastal bathymetry was obtained from the Bathymetric Model of Douro (IH). For both estuaries, additional ocean bathymetric data was extracted from the GEBCO database [69], and the different data sets considered were interpolated using a Kriging algorithm [70, 71].

The Douro River is one of the major rivers of the Iberian Peninsula. It flows from the Sierra de Urbion, in Spain, to the Atlantic Ocean, in northern Portugal, ending in an urban estuary surrounded by two major cities: Porto and Vila Nova de Gaia (**Figure 1**). The Douro is a highly dynamic narrow estuary with torrential regimes that produce strong currents and recurrent severe floods that cause serious damage to the riverine populations and navigation problems [68, 72]. Its dynamics is mainly forced by freshwater flows, being very dependent on highly variable natural conditions and on the hydropower production schedule of the Crestuma-Lever dam and of the other 50 national and international river basin dams. For flow rates above 800 m^3/s, the river water masses rush to the sea and seawater intrusion is prevented. For flow rates below 800 m^3/s, the ocean water enters the estuary, which acquires a salt-wedge configuration [73]. This has a strong effect on the freshwater residence time, which can vary from 8 h to more than 2 weeks [74]. The bathymetric configuration of the Douro estuary presents an irregular distribution with depths generally varying between 0 and 10 m (**Figures 1** and **3**). Depths up to 28 m can be found associated with narrower sections, outer bends, and former sites of sediments extraction [72]. At the southern margin of the estuary's mouth lies a wetland (São Paio Bay) and an estuarine sand spit (Cabedelo) that partially obstructs the river mouth, protecting the estuary from the ocean's storm waves. This sand spit is made up of fluvial and maritime sediments, and its morphodynamics is conditioned by natural (wind, rainfall, river flow, waves, tides and storm surges) and human (breakwaters and dams construction, sand extraction, and dredging) processes [68, 75, 76]. To prevent erosion of the sand spit or its excessive migration into the navigation channel, maintaining both navigability and bank protection, a new detached breakwater was built parallel to the head of the sandbar, and the existing northern breakwater was extended. These structures, concluded in 2008, interfere with local sedimentary and hydrodynamic patterns, significantly increasing the area and volume of the sand spit in a relatively short period (~10 years) [68, 77]. Historical records reveal ruptures or partial destruction of the sandbar during river flood events, allowing for a rapid discharge of excess

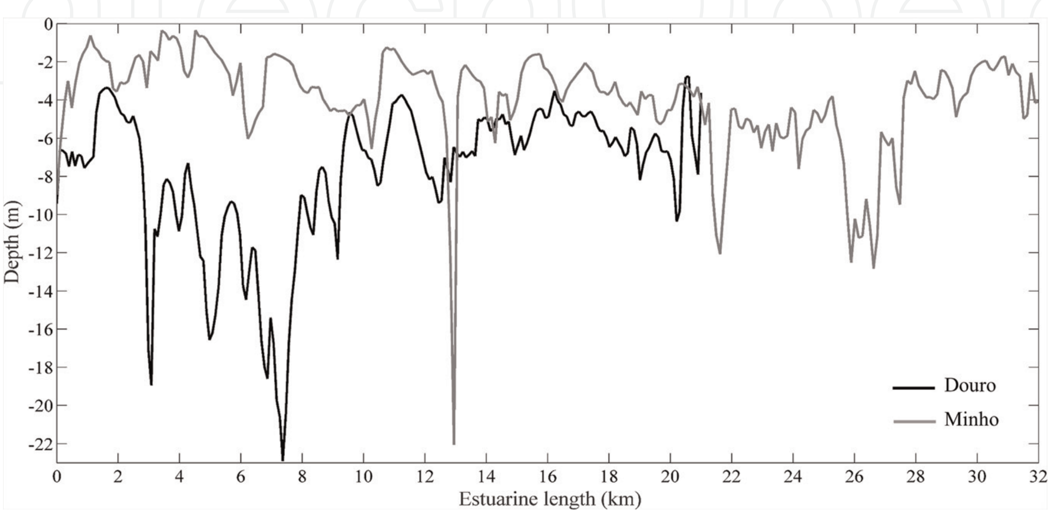

Figure 3.
Minho and Douro estuaries' bathymetric profile for the estuarine central axis (in metres—vertical datum MSL-mean sea level).

water and reducing the risk of urban flooding [68]. Now, with a stronger sandbar, its rupture is less probable and the effect of a flood is likely to be harsher, both in terms of economic losses and structural damage [14].

There are some previous works that aimed to reproduce the Douro estuary dynamics using numerical models. Silva [78] implemented a 2D depth-averaged (2DH) hydrodynamic model for the lower estuarine area, to represent the effect of several engineering works on the main currents configuration. Using the 1994 configuration, he found that relatively small alterations of the estuarine mouth conditions can produce marked changes in the currents strength and direction for normal winter conditions (river flow ~1000 m^3/s). The impact of the structures at the estuary's mouth on hydrodynamics, salt-water intrusion, and sediment transport was also presented by Pinho et al. [79], considering several scenarios of mean river flow. Their solutions, which were obtained using two coupled models: one for hydrodynamics and another for sediment transport, revealed maximum current velocities and maximum erosion at the estuarine mouth between the breakwaters. Similar patterns were obtained by Portela [72] and Iglesias et al. [14]. Particularly, Iglesias et al. [14] implemented two different numerical models for the Douro river to depict the effect of the sand spit in the floods water levels, demonstrating that the new breakwaters configuration and the strengthening of the sand spit will probably produce an increase in high-water levels during flood conditions, with expected severe impacts on the estuary banks. River floods were also simulated by Araújo et al. [80]. However, their work was focused on numerical model meshes development rather than on the socio-economical impacts of floods. Other related research are the modeling works of Azevedo et al. [81, 82], which related the estuary's hydrodynamic behavior with contaminant dispersion, biogeochemistry, and primary production, and the work of Mendes et al. [83], which evaluated the potential effect of sea-level rise in the Douro estuary.

The Minho River is an international river as well; it separates Spain and Portugal in its last 70 km, flowing into the Atlantic Ocean between A Guarda (Spain) and Caminha (Portugal). The Minho estuary is a very shallow water body, with a mean depth of 4 m, but regions close to 20-m depth can be found associated with a narrowing of the main channel, that increases flow velocities and, consequently, erosion (**Figures 1** and **3**) [84, 85]. Estuarine flows are mainly controlled by the Frieira dam, whose reservoir feeds a hydroelectric power plant located 80 km upstream from the estuary mouth. Due to the low river flow values (see **Figure 2**), the average water residence time in this estuary is 1.5 days [86]. The tributaries of the Minho between Frieira and the estuarine mouth can provide some additional freshwater to the estuary, but they have a minor influence given their small drainage basins.

One of the most important characteristics of the Minho estuarine region is its large diversity of habitats and its importance for the nursery and feeding of marine species and for ecosystem functioning [87, 88]. For this reason, this estuary is protected by Portuguese and Spanish conservation statutes, preserving a low level of industrialization. Despite the fact that the Minho ecosystem has been intensively studied in terms of its morpho-hydrodynamic characteristics, water quality, biodiversity, populations, and pollution, its dynamics is still essentially unknown [89, 90]. One of this estuary's main problems is the strong siltation related with high sediment deposition and low currents velocities, which are due to flow rate smoothing by the dam, and the consequent reduction of the frequency and intensity of floods [91, 92]. Being the hydrographic zero the level of the lowest astronomical tide, which is 2 m below the local mean sea level, the area above the hydrographic zero between the river mouth, and 14 km upstream represents about 70% of the total area, indicating a high degree of sedimentation. The morphodynamic patterns generated by silting produced several bathymetric constraints to navigation, such as strangulation or intense variations of bathymetry, and various islands and sandbars that emerge during low tide [85, 93]. Also, during the low water level period of spring tides, the connection between the estuary and the sea is restricted to two shallow channels, causing serious problems for navigation. Dredging campaigns are often carried out to keep the navigation channel open, with possible implications for the morphological evolution of the estuary and adjacent coastal areas [94], and for bottom habitats.

In terms of numerical modeling, there is a lack of publications for this estuary, probably due to the scarcity of *in-situ* data to force and calibrate the numerical models and validate their accuracy. Sousa et al. [95] and Pereira [13] implemented two hydrodynamic numerical models (MOHID and Delft3D) for the Minho estuary surroundings. In spite of obtaining interesting results in the validation processes with data from the Minho estuary measurement stations, those studies focused on representing the interaction between the waters of the Minho river and the Galician rias or the Lima estuary, respectively, and do not present a detailed and complete analysis of the estuarine hydrodynamics. Delgado [94] and Portela [92] also built some numerical modeling tools for the Minho estuary. Their studies focused mainly on the estuarine sediment transport for a few theoretical scenarios.

Nevertheless, several conclusions about the morpho-hydrodynamic behavior of the Minho estuary can be inferred from previous works. The estuarine processes may be dominated by the river flow or by the tide depending on the magnitude of these two forcing parameters. Extreme river flows can change the circulation pattern within the entire estuarine and coastal region, restricting the entrance of oceanic water to the mouth of the estuary. In such cases, the tide acts as a resistance to the fluvial flow. Current velocities of the ebb are higher than the velocity during flood, which produces a higher duration of the ebb. This effect is stronger for low river flows. As expected, currents exhibit higher velocities in the narrower sections, particularly at the mouth of the estuary, but they are also stronger during spring tides than during neap tides. The described hydrodynamic patterns will have a direct effect on sediment transport, which is directly proportional to the strength of the flow and the amplitude of the tide. Similar conclusions were obtained by Iglesias et al. [96] using realistic river flow and tide scenarios. Their numerical solutions show a tide dominated estuary, with a visible tidal effect even for extreme river flows. For low river flow conditions, a large part of the estuarine region is dry, becoming exposed to the wind action. In this situation, river flow is confined to two shallow channels in the estuarine area. During high flow conditions, most of the estuary is flooded, with intense currents throughout the estuarine region, except in the widest part upstream from the river mouth, where the estuary widens and the cross-sectional area increases significantly.

4. Discussion and conclusions

The characteristics of an estuarine region depend on numerous drivers that define not only the estuarine behavior, but also its ecosystems and human settlement distribution. In this chapter, these relationships, and differences between estuaries, are highlighted, comparing two near-by but completely different estuarine regions of the northern Portuguese coast. The comparison reinforces the need to analyze each region separately, considering the specific configuration of each estuary for the definition of management protocols, to minimize any potential vulnerability and to allow mitigation of risks and hazardous effects.

The Douro estuary is an urban estuary, where effects of extreme events, anthropic activities, and climate changes will mostly generate problems in urban environments, reflected in structural damages, economic losses, and impacts on tourism and navigation activities. In the Minho estuary, the same phenomena will have different impacts, mostly affecting ecosystems and biodiversity, due to habitat loss and the migration and loss of autochthonous species. In comparison to the Douro estuary, the Minho presents a smaller concentration of population and human activities on its banks. Thus, economic impacts will mainly be caused by changes in the fishing and tourism activities.

The modeling tools that have been developed so far, and which were described above, although extremely useful, need to be further developed. In the case of the Douro estuary, a complete hydrodynamic characterization, which considers the present topo-bathymetric configuration is still needed to fully unravel the estuarine dynamics, assess evolution trends, forecast future developments, including the effects of possible future human interventions, as well as to estimate the risks of flooding and the effect of sea-level rise associated with global warming. The numerical models developed for the Minho estuary are clearly insufficient for a complete characterization of this complex region, as well as for a reliable forecast of, for instance, hazardous events effects. Numerical models, capable of representing the estuarine stratification and its links with tide, river flow, and waves, are key tools to understand the distribution of biota and the functioning of the ecosystem, and to anticipate possible future conditions considering climate change and sea-level rise conditions. In addition, numerical models capable of representing the transport of larvae, pollutant, and sediments in a realistic way are crucial to describe estuarine trends, assess effects of anthropogenic intervention, quantify water residence times and sedimentary/erosive processes, as well as anticipate the effect of extreme river flows.

Next to stressing the relevance of performing regional modeling studies, this chapter also provides a thorough characterization of different available models, techniques, and physical processes simulations, including comparisons of several models performances, underlining the importance of choosing the modeling tool that best suits the numerical problem at hand and the computational means available to the user.

All these facts highlight the relevance of research projects dedicated to improve numerical modeling tools that provide a deeper understanding of the estuarine and coastal zones and represent the dynamics of the systems over time (past and present situations). One example is the project *EsCo-Ensembles—Estuarine and coastal numerical modeling ensembles for anthropogenic, extreme events and climate change scenarios*. This project aims to apply a new methodology based on models *ensembles* to build forecast and warning systems for estuarine/coastal regions. Two or more model outputs will be combined to obtain more accurate results that properly represent actual estuarine behavior as well as future trends, allowing for identification and mapping of the most sensitive areas. Modeling results will help to preserve and protect the estuarine/coastal regions and to mitigate the damages related with hazardous events, anthropogenic interventions, and climate change. Although extremely reliable, numerical models are prone to errors related to bathymetric and topographic assumptions, grid construction, spatial and temporal resolution, and to initial and forcing conditions, as well. As an example, there is not a clear trend for sea-level rise at the Portuguese coast. For different locations and periods, several authors report values of 1.3 [97], 1.9 [98], or even −0.7 mm/year [99], which does not agree with the global mean sea level rise of 1–2 mm/year, although locally, sea level can present increasing or decreasing trends [2]. To properly represent the effect of sea-level rise over the hydrodynamic conditions for a particular region, all these trends should be carefully evaluated and properly integrated into the numerical models. However, to avoid a large amount of input options, which can lead to inaccuracies in the numerical results, a models *ensemble* will be produced for the final forecasting. The *EsCo-Ensembles* project will provide valuable information about the NW Portuguese coastal zone to authorities, stakeholders, inhabitants, and society in general. Project results will contribute to the development of strategies for a sustainable management of estuarine and coastal areas affected by anthropogenic pressures, providing key information to develop protocols and mitigation strategies, to protect natural resources, population and infrastructures, and to potentiate new maritime infrastructures and coastal defense works adapted to future harmful events and climate change conditions.

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