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# Coupling Watersheds, Estuaries and Regional Oceanography through Numerical Modelling in the Western Iberia: Thermohaline Flux Variability at the Ocean-Estuary Interface

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Additional information is available at the end of the chapter

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## Abstract

The characterisation of the water and properties exchanges at the estuary-ocean interface is a key information to understand the estuarine plume influence on coastal circulation and in the generation of haline fronts. In this work, the largest eight Portuguese estuaries were modelled using the MOHID Water numerical model for the period 2010–2016. Water fluxes and associated properties were computed numerically at each of the estuary mouths. These results served to estimate the tidal prisms, tidal flows and to describe the annual evolution of water temperature and salinity. Those fluxes could serve to improve the land boundary conditions for regional ocean models. Moreover, the numerical analysis of the estuarine fluxes allow for the better characterisation of the studied systems, as two neighbouring estuaries could present very different fluxes and water properties. Where available, modelling results were compared with stations near the estuary mouth.

**Keywords:** Portugal, numerical modelling, MOHID, PCOMS, WIBP, salinity, estuarine fluxes, tidal prism, river

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## 1. Introduction

In Ref. [1], an estuary is defined as ‘a semi-enclosed coastal body of water, which has a free connection with the open sea, and within which sea water is measurably diluted with fresh-water derived from land drainage’. On its way to the open ocean, fresh water carried by rivers

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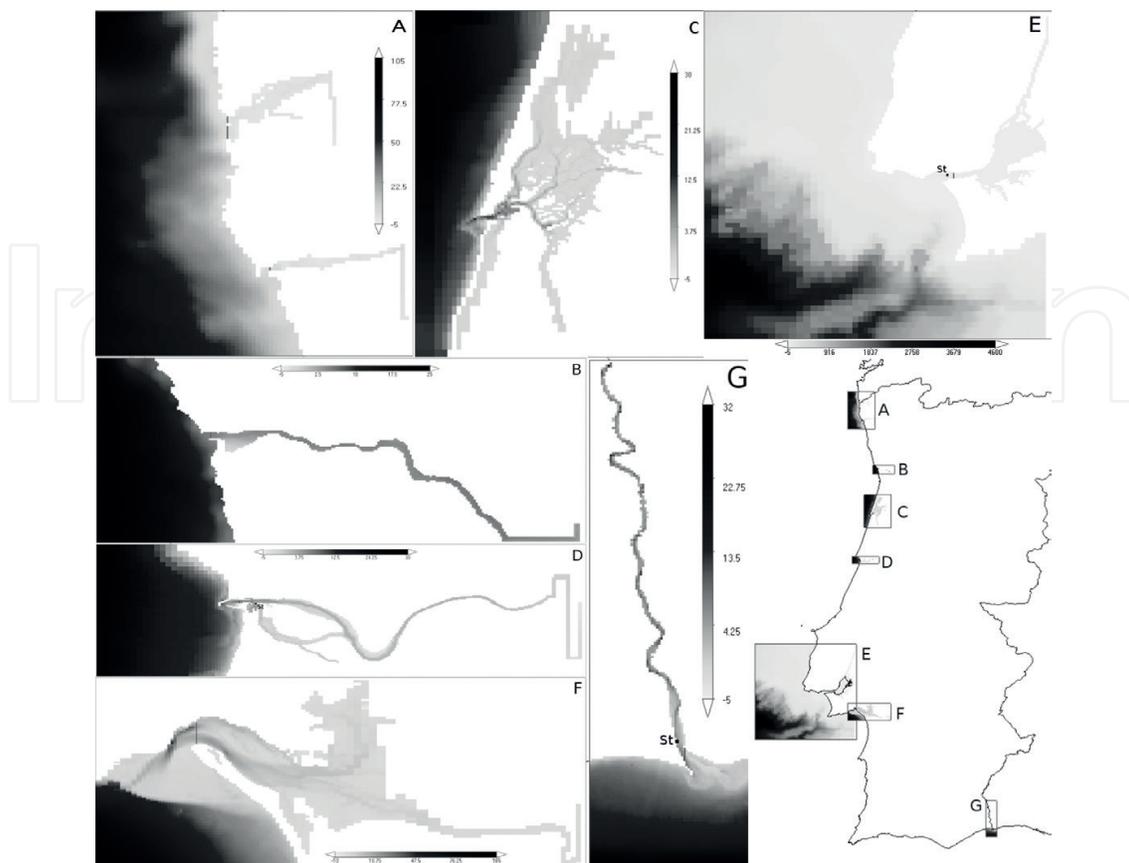
is mixed with the saltier ocean water aided mainly by the action of tides and atmospheric forces. The salinity of the estuarine fluxes that are incorporated in the near ocean depend on several factors including the estuary tidal prism and magnitude of river run-off. While the size of the tidal prism is controlled by the morphodynamics of each particular area, the fresh water inputs are controlled by natural factors such as rainfall and human fresh water management upstream the river mouth, i.e. water irrigation, storage for electricity and deviation to other watersheds. The natural and man-made variability of the fresh water volume and properties is a constraint to characterise the estuarine waters that flow from estuaries to the open ocean due to the lack of permanent monitoring stations. This characterisation is critical to understand their influence in coastal hydrodynamics and ecological processes.

From the European environmental legislation perspective, estuaries are typically regarded as transitional waters in the EU Water Framework Directive (WFD, Directive 2000/60/EC) and therefore may mostly fall outside the scope of EU Marine Strategy Framework Directive (MSFD, Directive 2008/56/EC). However, estuaries may have estuarine plumes which extend beyond transitional waters limit, 1 nautical mile from baseline, into coastal waters or beyond; in these cases, the estuarine habitat would fall within the scope of MSFD [2]. For this reason, the exclusion of estuaries and other transitional waters from the MSFD has been questioned [3]. In any case, though WFD requires the monitoring of several biological and chemical elements for the establishment of reference conditions in terms of water quality, long-term continuous monitoring with high temporal resolution are rarely deployed in estuaries [4] and, when deployed, some sensors have limited capabilities for longstanding observations [5]. For this reason, numerical models are able to support *in situ* monitoring by completing the datasets spatially and temporally and by contrasting the ambiguous observed values. Also numerical models can assist to describe the transitional waters including the extension and influence of the estuarine plumes in the near ocean.

In this chapter, the tidal prism and estuarine fluxes will be characterised with the aid of numerical models and the existing monitoring stations from the main Portuguese estuaries. This work also aims to describe in more detail the estuarine component of the methodology to couple watersheds, estuaries and regional oceans through numerical modelling for Western Iberia [6].

## 2. Study area

In this study, fluxes from the eight largest Portuguese estuaries were analysed. These were from North to South: Minho, Lima, Douro, Ria de Aveiro (hereafter referred as Aveiro estuary), Mondego, Tagus, Sado and Guadiana (**Figure 1**). All these estuaries are named after the main river discharging into the system with the exception of the Aveiro Estuary, where the principal fresh water source is the Vouga River. Their associated river catchments are distributed in areas with different climate characteristics; for example, the annual rainfall gradient between the two most distant rivers, Minho and Guadiana, which is around 1700 mm [7]. From an administrative point of view, Douro, Guadiana, Lima, Minho and Tagus are international rivers while the drainage areas of the Vouga, Mondego and Sado rivers fall entirely within Portuguese territory.



**Figure 1.** Bathymetry and model domain of the estuaries analysed in this work and its location in the Portuguese context (bottom right): (A) Minho (top) and Lima (bottom), (B) Douro, (C) Aveiro, (D) Mondego, (E) Tagus, (F) Sado and (G) Guadiana. In each estuary, a red line indicates the location of the cross-section where the estuarine fluxes were calculated. Monitoring stations in the Guadiana, Mondego and Tagus estuaries are indicated with 'St'.

### 3. Material and methods

#### 3.1. Monitoring networks

In order to validate the estuarine numerical model applications, automatic data collected along the estuarine continuum from hydrometric stations and estuarine buoys were gathered and analysed during this investigation. Hydrometric data provided reliable boundary conditions for the river, while the *in situ* estuarine data collected by the monitoring stations were used to validate the modelling results. Although influenced by the global decline context [8], the hydrometric network is a more stable and reliable source of data when compared to the long-term autonomous monitoring of estuarine systems which is generally scarce. In fact, none of the estuarine stations described below are currently in operation. Moreover, to guarantee high performance, the sensors equipped in the estuarine stations require periodic calibration [4]. For instance, the performance of temperature sensors are more reliable than salinity sensors [5].

The Portuguese river hydrometric observation network, forms part of the Portuguese Environmental Agency (APA, by its acronym in Portuguese), and is responsible for monitoring the fresh water flow in all the territory and data is made freely available in the SNIRH website

(<http://snirh.pt>). Reliable automatic stations for the study period were available in the Douro, Guadiana, Mondego and Tagus rivers and are Albufeira de Crestuma, 20 km upstream from Douro estuarine mouth, Açude de Pedrogão, 130 km upstream from Guadiana estuary mouth, Açude de Coimbra, 45 km upstream from Mondego estuary mouth, and Almourol, 130 km upstream from the Tagus estuary mouth. The location of these stations will exclude the contributions to the river flow due to rainfall and other minor tributaries between the station and the head of the estuary, which can be relevant in heavy rainy areas.

In Portugal, several estuaries were monitored continuously during the simulated period, 2010–2016. The SIMPATICO network comprising three *in situ* monitoring stations in the Guadiana (37.188°N, 7.411°W), Mondego (40.144°N, 8.856°W) and Tagus (39.058°N, 8.774°W) estuaries collected continuous water-quality and current data [4]. For the purpose of this study, only the Guadiana and Mondego observations from the SIMPATICO network are adequate, since the monitoring station in the Tagus estuary is located 40 km upstream from the Tagus mouth and thus unable to represent the estuarine mouth conditions. Instead, a monitoring buoy, hereafter referred as Algés buoy (38.694°N, 9.237°W), deployed by the water utility SimTejo was used to represent the Tagus water conditions in the estuary-ocean interface (**Figure 1**).

### 3.2. Numerical models

Each studied estuary was simulated for the period 2010–2016 using the MOHID Water model. The MOHID Water model is an open-source numerical model included in MOHID Water Modelling System (<http://www.mohid.com>; [9]) developed continuously since 1985 mainly at the Instituto Superior Técnico (IST) from the Universidade de Lisboa. The model adopted an object oriented philosophy model for surface water bodies that integrates different scales and processes using finite volumes. The core of the model is a fully 3D hydrodynamic model which is coupled to different modules comprising among others water quality, atmosphere processes, discharges, oil dispersion, mixing zone model for point source discharges. The MOHID Water model has been applied to many coastal and estuarine areas worldwide and has shown its ability to simulate successfully very different spatial scales from large coastal areas to coastal structures.

For this study, most of the estuarine modelling applications were simulated using modelling grids, domains and bathymetries from previous studies (**Table 1**). The bathymetries of the Minho, Lima and Sado estuarine model applications were updated on their ocean side using improved global bathymetric databases such as the EMODnet-Hydrography portal (<http://www.emodnet-hydrography.eu>). Only the Guadiana estuary model domain was fully developed for this study, using a 100 m resolution bathymetry model for the Guadiana estuary provided by the Instituto Hidrográfico (<http://www.hidrografico.pt>).

Boundary conditions were updated for most of the applications; on the ocean side, the estuarine models were nested to the Portuguese Coast Operational Modelling System (hereafter referred as PCOMS; [10]), following the downscaling methodology described in Ref. [11]. On the landward side, Douro, Guadiana, Mondego and Tagus estuaries were forced by river flow data obtained from the closest stable monitoring station from the Portuguese river hydrometric observation network (<http://snirh.pt>; **Table 1**). Due to the limited data available for the rivers discharging in the Aveiro, Lima, Minho and Sado estuaries, flow data were obtained from a

Estuary	Mouth Location		Horizontal resolution	Dimension (cells number)		Meteorology model	Fresh water sources	References
	Lat.	Long.		Zonal	Meridional			
Aveiro	40.645°N	8.740°W	0.0022*	87	81	MM5 IST-9 km	<b>Model:</b> Vouga MOHID Land <b>Climatology:</b> Antuã, Boco, Caster and Mira rivers	Saraiva [17] and Sobrinho [18]
Douro	41.146°N	8.671°W	0.0010	244	115	WRF MG-4 km	<b>SNIRH:</b> Albufeira de Crestuma station	Kenov I. (Pers. Comm.)
Guadiana	37.178°N	7.405°W	0.0018	70	221	MM5 IST-9 km	<b>SNIRH:</b> Pedrogão station	developed for this study
Lima	41.686°N	8.835°W	0.0040	70	105	WRF MG-4 km	<b>Model:</b> Lima MOHID Land	updated from Saraiva et al. [19]
Minho	41.858°N	8.875°W					<b>Model:</b> Minho MOHID Land	
Mondego	40.145°N	8.866°W	0.0035	206	97	MM5 IST-9 km	<b>SNIRH:</b> Açude de Coimbra station	Kenov et al. [20]
Sado	38.503°N	8.905°W	0.0060	94	90	MM5 IST-9 km	<b>Model:</b> Sado MOHID Land	updated from Martins et al. [21]
Tagus	38.685°N	9.222°W	0.0027*	145	120	WRF IST-3 km	<b>SNIRH:</b> Almourol station <b>Climatology:</b> Sorraia and Trancão rivers <b>Constant:</b> UWWTPs of Alcântara, Beirolas, Chelas, S. João da Talha and Guia	Fernandes [22] and Campuzano et al. [11]

Cross-section estuarine fluxes are calculated along the defined longitude while latitude indicates the centre of the mouth section. Observations were obtained from the SNIRH web portal (<http://www.snirh.pt>) and model results were obtained from the West Iberia domain (WI MOHID Land model application) described in Ref [12].

\*The zonal resolution at the mouth in irregularly sized grids.

**Table 1.** Estuary mouth coordinates, horizontal resolution, model domain dimension, sources of meteorological forcing and fresh water and previous model description reference.

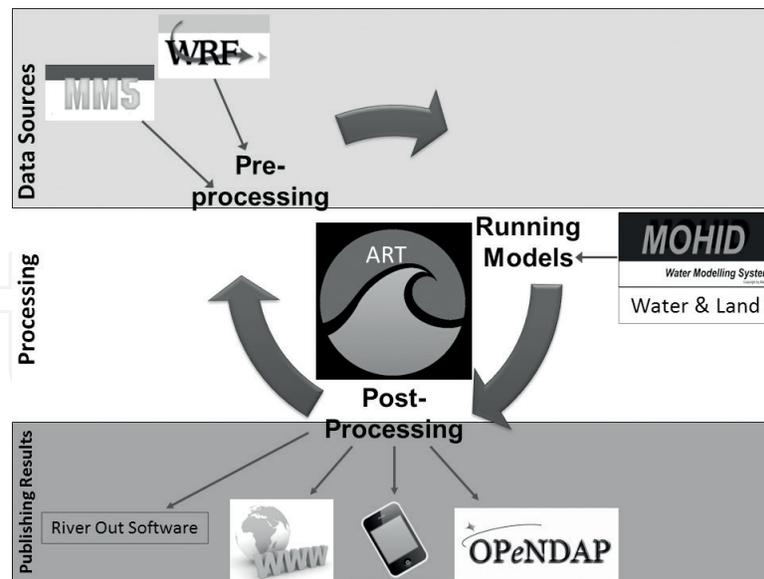
watershed model for West Iberia with 2 km horizontal resolution (WI MOHID Land) described in Ref. [12]. Monthly climatology river flow or constant values were only used for other minor sources of fresh water, the Pranto river for the Mondego estuary, four for the Aveiro estuary and two rivers and 14 urban waste water treatment plants (UWWTPs) for the Tagus estuary. As monitoring stations providing reliable and regular water properties were absent for many of the rivers, water temperature in all the estuarine applications was obtained from the WI MOHID Land model application and river salinity was considered as pure fresh water.

All the estuarine models were implemented in 2D depth integrated domains except for the Tagus application, hereafter referred as TagusMouth, which is a fully 3D baroclinic hydrodynamic and ecological application. The TagusMouth vertical discretisation consists of a mixed vertical geometry which is composed of a sigma domain with 7 layers from the surface until 8.68 m depth, with variable thickness decreasing up to 1 m at the surface, on top of a Cartesian domain of 43 layers with thickness increasing towards the bottom.

Each estuarine application was forced with the higher horizontal resolution meteorological model available for its domain. Meteorological model applications provided 3D fields that included relevant model forcing variables (i.e. precipitation, solar radiation, wind modulus and direction, relative humidity, air temperature, etc.) and whose surface layer is interpolated for each modelling domain by triangulation. The Minho, Lima and Douro estuaries were forced using WRF model results [13] with 4 km horizontal resolution generated by Meteogalicia (MG, <http://www.meteogalicia.es>). The TagusMouth model application is forced using 3 km horizontal resolution WRF model results provided by the IST meteorological group (IST, <http://meteo.tecnico.ulisboa.pt>). The Aveiro, Guadiana, Mondego and Sado modelling domains used, as atmospheric boundary conditions, MM5 modelling results [14] with a horizontal resolution of 9 km provided also by the IST meteorological group [15].

This set of numerical models was integrated and synchronised through the ART software (Automatic Running Tool; **Figure 2**), a software for the automation of model simulations developed at IST that is currently used by many operational applications [6, 12, 16]. The ART tool is a standalone application, independent, compiled, and able to run in any Windows operative system. This tool can be seen as the 'heart' of an operational framework, controlling the execution of other auxiliary standalone applications or even scripts (e.g. conversion of file formats, interpolation and specific downloading procedures), adapting automatically the configuration files and launching those applications. The ART tool pre-processes the boundary conditions from different sources needed to run the model, and executes the MOHID Water and Land model applications using the configured files. After each estuarine model has concluded, it executes the River Out software, a software designed specifically to extract and calculate the water fluxes and concentrations for all the cells comprised at a fixed longitude and between two defined latitudes and to store them in an organised manner.

**Table 1** summarises the main characteristics of the estuarine model applications including the modelling domains, their location of their mouth where the fluxes were calculated, the source of fresh water forcing and the reference of the previous study. Most of the numerical models here described are currently running operationally in the MARETEC research centre (<http://forecast.maretec.org>).



**Figure 2.** General scheme of the Automatic Running Tool (ART) depicting the pre-processing, modelling and post-processing cycle of operations with the elements used for the MOHID Land and MOHID Water applications used in this work. The River Out software is executed during the post-processing operations of the estuarine model application.

## 4. Results and discussion

In Portuguese estuaries, the ocean and fresh water mix are controlled by the tidal regime, estuary geomorphology and river discharge. A useful parameter to characterise the estuaries by the tidal regime and the geomorphology is the tidal prism. The tidal prism, as defined by [23], is ‘the amount of water that flows into and out of an estuary or bay with the flood and ebb of the tide, excluding any contribution from freshwater inflows’.

The defined cross-sections serve to estimate numerically and accurately the amount of water flowing through the estuarine mouth and thus to estimate tidal prisms. Tidal prism volumes were calculated by integrating the hourly ebb and flood flows for each tidal cycle. For each estuary, mean tidal prism values were obtained considering the entire dataset and differentiating between ebb and flood conditions obtaining volumes with a similar order of magnitude than the ones found in the literature (**Table 2**).

The volume of water discharged by the river affects the duration and intensity of the flood and ebb tides. Ebb tidal prisms are generally larger as they include the river flow in addition to the flushing tide. Furthermore, high river discharges constraint the beginning of the estuary flooding. The difference between flood and ebb tidal prisms is larger in estuaries with low tidal prism and high river discharge such as that in the Douro estuary. When the Douro river flow is removed from the fluxes calculation, the obtained tidal prisms present similar volumes for both flood and ebb tides, estimated at around  $1.21 \times 10^7 \text{ m}^3$ . As can be seen in **Table 2**, the Douro estuary can be defined as an extreme case for Portuguese estuaries, as in the remaining systems, the rivers do not appear to influence the tidal prism and differences between ebb and flood are similar. For instance, the tidal prism of the Ria de Aveiro without the Vouga river discharge was  $6.81 \times 10^7 \text{ m}^3$  which is close to the mean tidal prism volume.

Estuary	Mean TP ( $\times 10^7 \text{ m}^3$ )	Flood Mean TP ( $\times 10^7 \text{ m}^3$ )	Ebb Mean TP ( $\times 10^7 \text{ m}^3$ )	Flow std. deviation ( $\sigma$ ) ( $\text{m}^3 \text{ s}^{-1}$ )	TP Reference volume ( $\times 10^7 \text{ m}^3$ )
Aveiro	$6.83 \pm 1.82$	$6.61 \pm 1.86$	$7.04 \pm 1.76$	3518.92	6.00 [24] 7.00 [25] 11.90 [26]
Douro	$2.20 \pm 12.23$	$0.83 \pm 0.49$	$3.56 \pm 23.97$	875.99	0.55 [27] 2.09 [26]
Guadiana	$2.96 \pm 1.74$	$2.73 \pm 0.74$	$3.19 \pm 2.73$	1467.16	0.60 [26]
Lima	$1.24 \pm 0.57$	$1.08 \pm 0.52$	$1.40 \pm 0.61$	749.74	0.90 [26]
Minho	$3.10 \pm 1.53$	$2.79 \pm 1.39$	$3.41 \pm 1.66$	1612.07	0.55 [26]
Mondego	$1.53 \pm 0.86$	$1.41 \pm 0.52$	$1.64 \pm 1.10$	802.58	0.99 [28]
Sado	$29.93 \pm 7.98$	$29.83 \pm 7.95$	$30.02 \pm 8.00$	15,064.64	40.00 [29]
Tagus	$62.47 \pm 15.96$	$62.01 \pm 16.50$	$62.93 \pm 15.42$	31,753.82	75.00 [30]

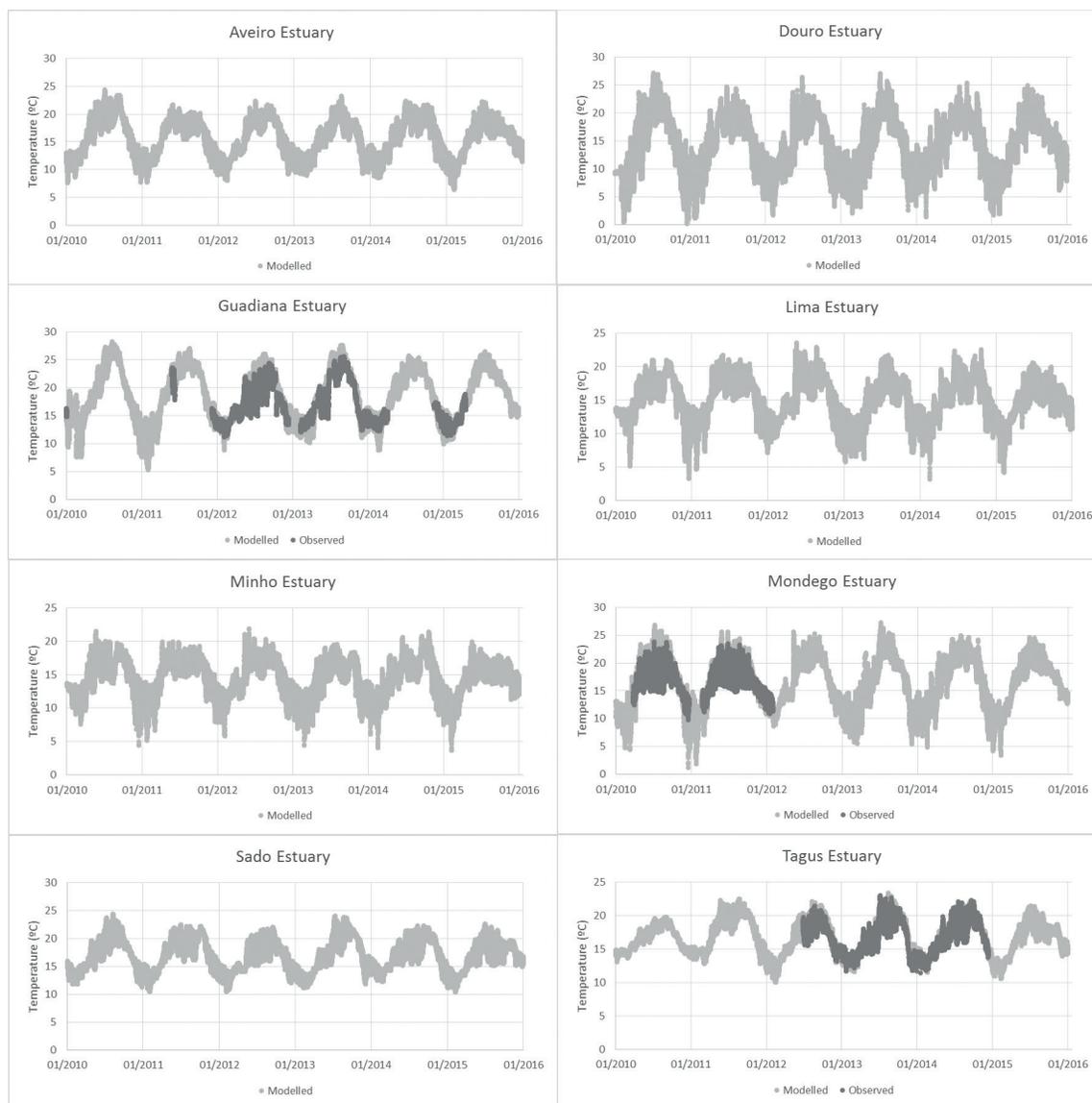
The table also included the estuarine flow standard deviation considered as an indicator of the flow at the ocean-estuary interface.

**Table 2.** Tidal prism (TP) for the entire study period and distinguishing between flood and ebb periods for each of the estuarine systems and bibliographic reference volumes.

As the estuarine fluxes changes during ebb and flood conditions, the net flux is similar to the river flow and always towards the ocean. However, the discharge momentum is far more intense than the river flow and evolves over time following the spring and neap tidal cycles. In order to provide a statistical indicator of the exchanged flow with the ocean, the standard deviation ( $\sigma$ ) can be employed as an indicator of the mean volume exchange at the estuarine mouth and  $\pm 2\sigma$  would result in the average maximum volume that circulates through the estuarine-ocean connection (**Table 2**). This value allows one to determine the magnitude of the exchanged flow and the influence in the neighbouring ocean circulation. The Tagus estuary exchange flow is larger than all the other estuaries combined (around  $24,000 \text{ m}^3 \text{ s}^{-1}$ ), followed by the Sado and Aveiro with half and a tenth of the Tagus flow, respectively.<sup>1</sup> On average, the total flow from the eight estuaries to the neighbouring ocean is around  $55,000 \text{ m}^3 \text{ s}^{-1}$ .

Depending on the tidal prism and the volume of river discharge, the properties of the water exchanged with the coastal area fluctuates. **Figures 3** and **4** indicate the evolution of the mean modelled temperature and salinity in each of the estuaries during the study period. Temperature and salinity values shown for the Tagus estuary in these figures correspond to its surface layer and therefore can be directly compared with the observations. In the rest of model applications, since they are bidimensional, temperature and salinity represent the vertically integrated values for the entire water column.

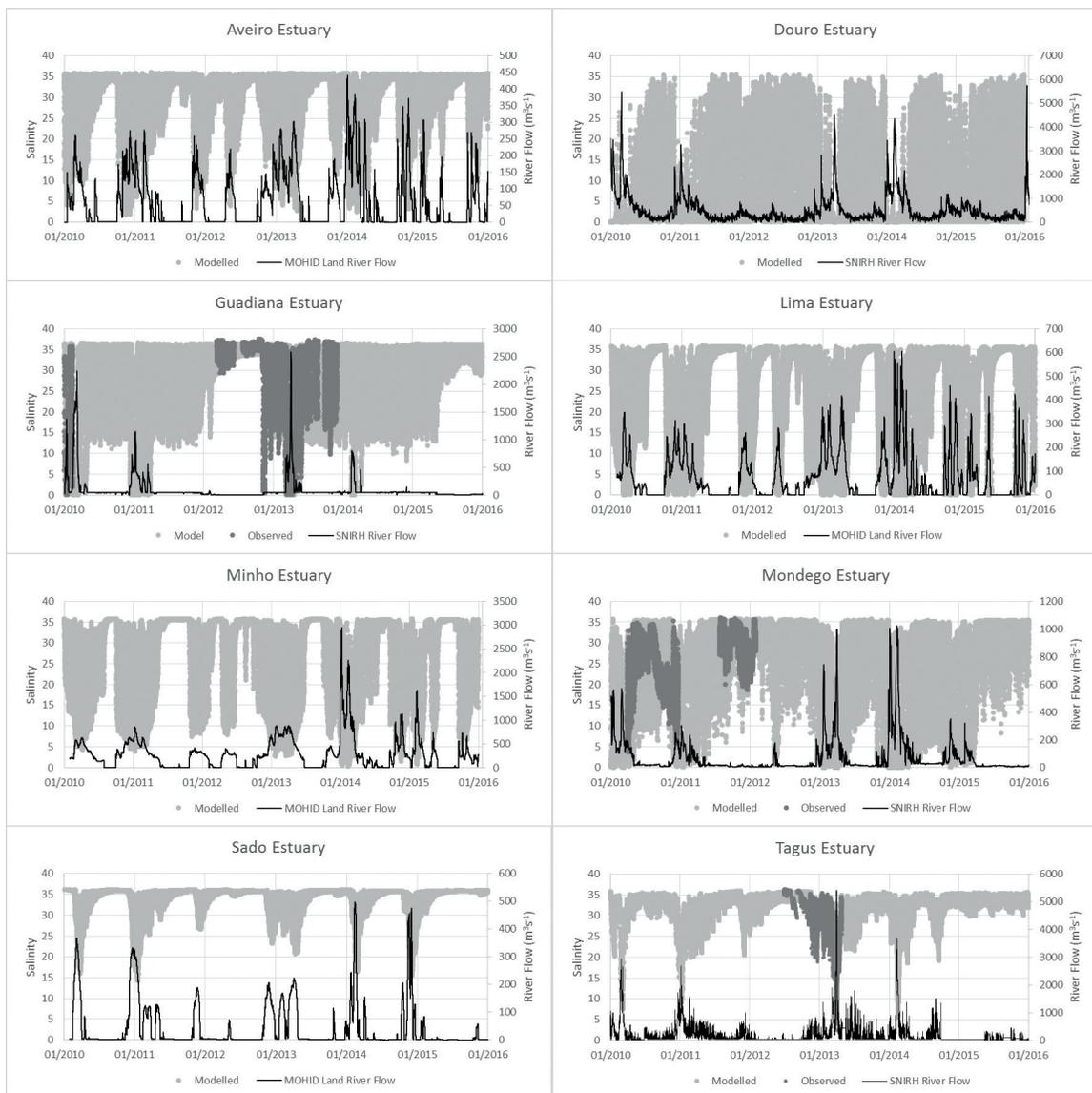
Surface water temperatures in the Atlantic Ocean around Portugal show a clear seasonal pattern with maximum temperatures during the summer months (JJA) and lower temperatures in winter (DJF) (**Figure 3** and **Table 4**). In tidally dominated estuaries, i.e. large tidal prism, temperature variations are reduced as ocean surface temperatures fluctuate less. For example, the water fluxes temperature for the Sado and Tagus estuaries range between 10 and  $25^\circ\text{C}$ , while in



**Figure 3.** Mean temperature of the water fluxes at the estuarine mouth cross-section. The graphs show the mean modelled value (in grey) for each estuary and for the entire period 2010–2016 and, where available, the observed data is also shown (in orange). The Tagus estuary values correspond in this graph to its surface layer. Estuaries are ordered alphabetically from top to bottom.

the Douro, Lima and Mondego estuaries, water temperature variations are generally less than 5°C. The river effect in the fluxes temperature is more recognisable during the winter period (DJF), as during this season, inland temperatures are lower and the river flow is higher.

The impact of river flow on the estuarine fluxes is most pronounced for salinity and is consistent with the different types of estuary (**Figure 4**). Estuaries with large tidal prisms, such as Sado and Tagus, present salinity concentrations greater than 0 even during high river flows such as the Tagus flooding event of April 2013. On the other hand, the Douro estuary exchanges fresh water with the near ocean on multiple occasions during every season and as a consequence, its fluxes present a mean salinity around 11 (**Table 5**). Guadiana, Lima and Mondego estuaries



**Figure 4.** Mean salinity of the water fluxes at the estuarine mouth cross-section. Graphs show the mean modelled value (in grey) for each estuary and for the entire period 2010–2016 and, where available, the observed data is also shown (in orange). The Tagus estuary values correspond in this graph to its surface layer. The river flow imposed in the model is displayed with a continuous black line and a secondary axis value and indicated whether the sources are observations (SNIRH) or watershed model results (MOHID land). Estuaries are ordered alphabetically from top to bottom.

exchange fresh water fluxes periodically every winter period only with the exception of year 2012 which was an extremely dry year. **Figure 4** shows the spatial heterogeneity of rain patterns since high river flows and events are not simultaneous in all the studied estuaries.

As mentioned above, three estuaries, Guadiana, Mondego and Tagus, had monitoring devices near the mouth of the estuary during the study period. The Algés buoy was monitoring near the Tagus estuary mouth for the period 27/06/2012 to 12/12/2014. The SIMPATICO station for the Mondego estuary collected data between 30/10/2007 and 02/02/2012 while in the Guadiana estuary, data was available for the period 19/03/2008 to 21/04/2015. The SIMPATICO dataset collected at the Guadiana estuary until April 2014 [5], is publicly available in machine-readable format at PANGAEA (DOI: 10.1594/PANGAEA.845750).

As discussed earlier, temperature sensor performance is more reliable than salinity sensors during long-term deployment. In that sense, the Guadiana estuary valid temperature data were 99%, while salinity valid data were 67.1% [5] with 20% of invalid data and 12.9% of ambiguous data. Also in the Tagus estuary, the Algés buoy salinity values were identified as valid until 30/04/2013 after which time the sensor calibration was lost. Valid temperature and salinity data for the three monitoring stations are represented in **Figures 3** and **4**. When compared with the modelled data, the coefficient of determination for temperature is higher than that for salinity at each station and the best model performance were for the Guadiana and Tagus estuaries (**Table 3**). The Mondego estuary coefficient of determination is lower in the SIMPATICO station compared with the other two estuaries. A possible reason is its location in the entrance of the southern branch ([4]; **Figure 1**) that could also be influenced by the Pranto River, which was simulated using a river flow climatology and may not be so representative of the main fresh water entrance that take place in the northern branch. It should also be noted that this is a comparison between the observed data at the surface with depth-integrated modelling results.

From the modelling results, a preliminary climatology of water temperature and salinity in the ocean-estuary interface can be obtained, which illustrate their variability along the year and provide a global picture of the thermohaline fluxes from the Portuguese estuaries. **Tables 4** and **5** list the monthly averaged temperature and salinity, respectively, calculated by the model at the ocean-estuary interface for the period 2010–2016 (**Figure 5**). February is the month presenting coldest temperatures for all the estuaries, while the warmest months occur between July (i.e. Douro) and October (i.e. Minho). The estuary location influences the summer maximum temperature as western Iberia coast is subjected to upwelling events during summer that bring cold nutrient-rich waters to the ocean surface. Thus, winter temperatures provide a more accurate reflection of the river discharges contribution to the estuarine water as it coincides with the rainy season. As a result, it can be concluded that the salinity concentrations of the Douro and the Tagus estuaries are, on average, the most and least influenced by river discharge, respectively.

Salinity is a more conservative indicator to study the river effect, as the salinity values in the near ocean vary little and is unaffected by the upwelled waters. Fluxes from Sado and Tagus estuaries could be categorised as saline because monthly averaged salinities were always >30. Generally, the Aveiro estuary exchanges saline waters during summer and autumn months and brackish waters, with salinities between 5 and 30, during winter and spring months while the Lima, Minho and Mondego estuarine mouths are dominated by brackish waters year round. Fresh water, (salinities <5), was recorded at the mouth of the Douro estuary during three first months of the year and, on average, maximum salinity observed during August is

Estuary	Temperature R <sup>2</sup>	Salinity R <sup>2</sup>
Guadiana	0.90 (N 21,435)	0.74 (N 12,057)
Mondego	0.79 (N 14,741)	0.32 (N 14,741)
Tagus	0.92 (N 20,944)	0.83 (N 7377)

The number of valid values is indicated in brackets.

**Table 3.** Coefficient of determination (R<sup>2</sup>) between the modelling results and the available observed data for the Guadiana, Mondego and Tagus estuaries.

Month	Aveiro	Douro	Guadiana	Lima	Minho	Mondego	Sado	Tagus
January	11.82	9.01	13.44	11.16	11.60	11.57	13.68	13.72
February	11.28	8.42	12.83	10.83	10.92	11.15	12.96	13.07
March	12.76	10.76	13.86	12.36	12.18	12.83	14.12	13.98
April	14.96	13.97	16.60	14.86	14.17	15.69	15.86	15.63
May	16.67	15.84	19.19	16.42	15.37	17.82	17.29	17.04
June	18.07	18.03	21.51	17.58	16.16	19.65	18.56	18.10
July	18.51	19.38	23.81	17.83	16.17	21.07	19.57	18.76
August	18.56	19.16	24.59	17.51	15.88	21.24	19.61	19.20
September	18.89	18.74	23.77	18.06	16.86	20.97	19.96	19.77
October	18.04	16.74	21.29	17.15	17.12	19.15	19.59	19.31
November	15.08	12.27	17.60	13.67	14.50	15.23	17.07	17.17
December	12.96	9.87	14.79	11.86	12.60	12.38	14.75	14.92
Average	15.66	14.38	18.64	14.96	14.48	16.66	16.94	16.81
Range	7.61	10.96	11.76	7.23	6.20	10.09	7.00	6.70

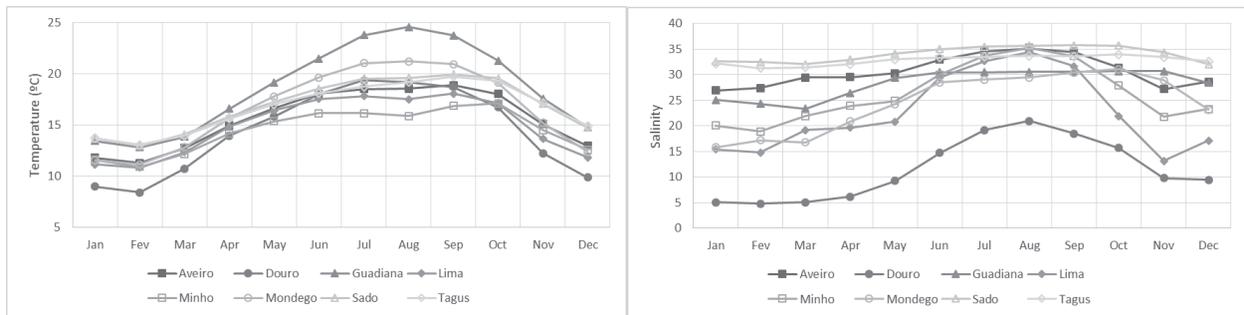
The average value and the range of values are also indicated.

**Table 4.** Mean monthly modelled temperature for eight analysed estuaries calculated at the ocean-estuary defined cross-sections during the 2010–2016 period.

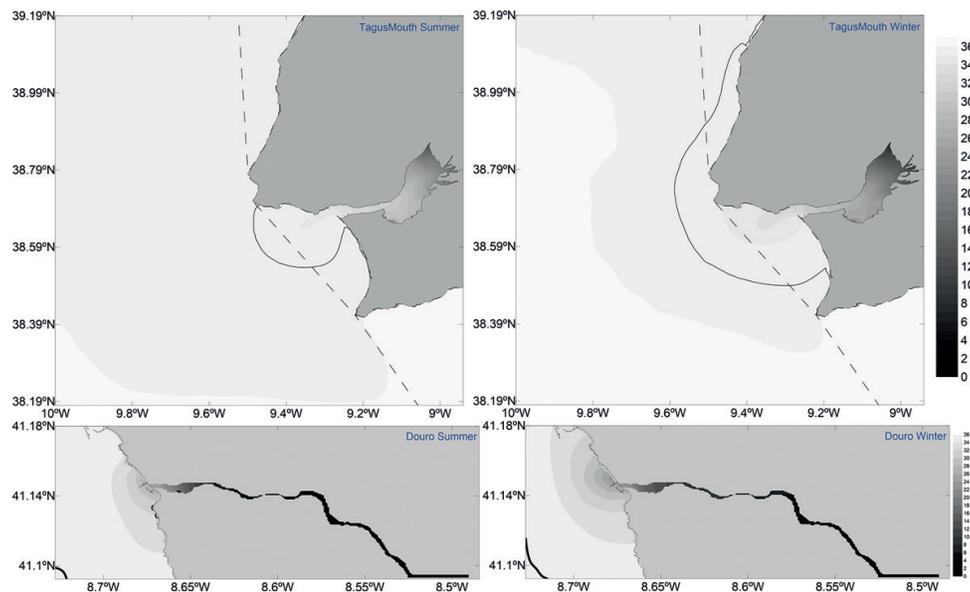
Month	Aveiro	Douro	Guadiana	Lima	Minho	Mondego	Sado	Tagus
January	26.91	5.12	25.08	15.45	20.12	15.88	32.61	32.20
February	27.41	4.81	24.36	14.81	18.92	17.24	32.51	31.31
March	29.50	5.10	23.38	19.22	21.92	16.79	32.05	31.47
April	29.51	6.19	26.47	19.65	23.91	20.92	32.95	32.09
May	30.27	9.25	29.41	20.86	24.90	24.25	34.14	33.05
June	32.94	14.75	30.49	29.51	29.99	28.53	35.01	33.37
July	34.52	19.19	30.52	32.68	33.74	29.05	35.51	33.52
August	35.15	20.97	30.55	34.38	35.27	29.46	35.73	33.75
September	34.46	18.53	30.64	31.65	33.69	30.46	35.80	33.55
October	31.42	15.71	30.71	21.97	27.89	31.15	35.73	33.97
November	27.19	9.80	30.68	13.17	21.83	28.95	34.43	33.44
December	28.68	9.50	28.42	17.16	23.30	23.17	32.10	32.64
Average	30.66	11.58	28.39	22.54	26.29	24.65	34.05	32.86
Range	8.25	16.16	7.33	21.21	16.35	15.28	3.75	2.67

The average value and the range of values are also indicated.

**Table 5.** Mean monthly modelled salinity for eight analysed estuaries calculated at the ocean-estuary defined cross-sections.



**Figure 5.** Mean monthly temperature (left) and salinity (right) obtained by numerical modelling at the estuarine mouth for eight Portuguese estuaries for the period 2010–2016.



**Figure 6.** Mean summer (JJA) salinity (left) and winter (DJF) salinity (right) for the Tagus (top) and Douro (bottom) estuaries for the period 2010–2016. The continuous line indicates the salinity value of 35.75. Dashed line in Tagus graphs indicates the baseline for defining internal waters.

still far from what is considered as saline. Still, the highest ranges of salinities at their mouths are observed in the Lima estuary followed by the Douro estuary and far from the very stable Sado and Tagus estuaries.

The salinity differences between the estuarine fluxes and the ocean saline waters are responsible for generating fronts of different intensity that can influence the surface circulation of large coastal areas. In the Northern half of Portugal, the high frequency of occurrence of rivers and estuaries is responsible for modifying local and coastal circulation contributing to the creation of haline fronts. As a result, a low salinity water lens, upper salinity limit below 35.7–35.8, denominated as Western Iberia Buoyant Plume (WIBP), extends along the northern Portuguese coast, being referred as a permanent feature of this part of the coast and with a varying intensity along the year [31, 32].

To illustrate the influence of the estuarine plumes on the near-shore ocean environment, the salinity average for the Douro and the Tagus estuary, the two most extreme estuaries of the study in terms of saline concentration, was obtained for the winter (DJF) and summer (JJA) seasons for the period 2010–2016. Both systems are characterised by large plumes in both seasons with salinity values below the WIBP upper limit (37.75) in the nearshore marine environment (**Figure 6**). The baseline in the Douro region that serves to identify the interior waters is out of the study domain. On the other hand, the Tagus plume extends further than the 1 nautical mile limit from baseline, the limit of the application of the MSFD and WFD, even during summer conditions. In the case of the Minho, Lima, Aveiro and Guadiana estuaries, the adopted baseline for the WFD and MSFD limit coincides with the coastline. For this reason, it is presumed that the estuarine plumes will have an effect beyond 1 nautical mile. This finding has implications for the implementation and evaluation of both EU Directives Research on estuarine plumes extension and their influence in the neighbouring waters is therefore essential.

## 5. Conclusions

Monitoring networks along the estuarine continuum from the river catchment into the open ocean should be encouraged in order to evaluate the transfer of properties and momentum in the land-ocean interface. While the open ocean and hydrometric monitoring networks are relatively well established, operational estuarine monitoring is far from consolidated. Numerical models are able to help in the design and implementation of the monitoring networks, validation of observed data and provide spatial and temporal data. In addition, numerical model completes the *in situ* data by providing non-observed variables and forecasts. Furthermore, modelling results allow for the calculation of complex parameters such as tidal prisms, the area of influence of the estuarine waters and estuarine fluxes that would serve as boundary conditions for ocean regional models such as the offline coupling method applied to PCOMS [6]. This type of analysis provides valuable information to characterise the estuarine systems, as this was able to show that two neighbouring estuaries can differ largely in flow and salinity fluxes.

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