



# Article Hydrodynamic and Sediment Transport Patterns in the Minho and Douro Estuaries (NW Portugal) Based on ADCP Monitoring Data: Part 1-Tidal Sediment Exchanges

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**Abstract:** The tidal variability of the Minho and Douro lower estuaries (NW Portugal) water column structure was assessed at the semi-diurnal and fortnightly time scales under two contrasting seasonal river flow scenarios during the summer of 2005 and winter of 2006. Sediment fluxes inferred from calibrated ADCP acoustic backscatter revealed that, during spring tides and low runoff conditions, both estuaries act as sinks instead of sources of sediments into the inner shelf. Sediment export occurred during neaps, in both estuaries, when the river flow values were high enough to counteract the effect of the entering flood. No evidence of coarse sediment export into the inner shelf that would eventually nourish the littoral system could be inferred from these datasets.

Keywords: estuarine dynamics; sediment transfers; acoustic backscatter; Minho; Douro

## 1. Introduction

Estuaries are complex systems wherein coupled geological, hydrodynamic, and biochemical processes interact with each other, the fluvial watershed, and the coastal zone, modulated by several forcing agents [1]. Anthropogenic activities also have significant impacts on the evolution of estuarine regions, changing the timing, magnitude, and nature of material inputs to estuaries [2]. Among these activities, dam construction has the most impact on estuarine morphodynamics. In Portugal, as in many other countries, most river systems are subject to flow regularization and hydropower production through the construction of dams and reservoirs [3–5]. Such structures are responsible for significant changes in estuarine configuration, modifying the natural discharge patterns, producing changes in sediment, organic matter, and nutrient transfer, and trapping the fluvial sediments upstream and, thus, decreasing the fluvial contribution to coastal sedimentary dynamics. When river flows are heavily controlled, natural flood discharge flows are avoided for population security. This trend may cause marine sediments transported by tidal flows to deposit inside the estuaries due to the lack of strong currents, resulting in significant changes in estuarine bathymetry [1].

The Portuguese littoral displays an overall regressive trend that has been documented since the end of the 19th century. This behavior has been recognized to be related to the sediment supply reduction due to human intervention, again due to the damming of rivers, sand extraction in water lines and reservoirs, agricultural practices aiming at soil conservation, and the construction of coastal engineering structures [3,6]. As a result, 25% of the Portuguese coastal zone is affected by intense coastal erosion phenomena, with a potential risk of territory loss in about 67% of the coastline, representing severe social



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**Copyright:** © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). and economic consequences given that 85% of the Gross National Product is generated in this area.

In 2014, following a particularly harsh winter, which caused a pronounced retreat of the coastline in some areas, the Portuguese Government officially recognized the urgency of the State intervention in this matter, constituting a work group of national experts from several Governmental institutions [7]. This work group's final report recognized that the construction of hydraulic infrastructures, like dams in rivers, have caused a significant decrease in the amount of sediments that, in the geological past, flowed into the sea and consequently would act as a source to the coastal zone. In this context, the Portuguese NW littoral has been especially prone to severe erosion rates, sometimes in the order of 8  $m/yr^1$  [8]. In its final recommendations, the work group emphasized that the mitigation of coastal erosion should address the causes as opposed to their consequences in this case of the existence of a severe sediment deficit.

Five major rivers supply the NW Iberian margin with sediment: Douro, Ave, Cávado, Lima, and Minho, between the latitudes of the city of Porto (Portugal) and Cape Finisterre (Spain), and, up to the 1950's, fluvial discharge was believed to be the main source of sediment in this segment of the coast. In this context, the Douro was widely recognized in the scientific community as the main source of sediment into the inner continental shelf and coastal zone [9–11]. However, the Douro's main course as well as its main tributaries have been subject to artificialization and intense human intervention in the past century, with a documented decrease in the average monthly river flow of the Douro from 715 m<sup>3</sup>/s (data from 1933 to 1985) down to 421 m<sup>3</sup>/s (1985–1994) after the construction of the Crestuma-Lever dam, which marks the artificial upper limit of the Douro estuary [12]. The work group's final report indicated annual solid export values from the Douro that range from  $3-18 \times 10^5$  m<sup>3</sup>/year of bedload (sand) transport in its natural state (before human intervention), decreasing to  $2-3 \times 10^5$  m<sup>3</sup>/year in its present artificialized state. No documented decrease in mean river flow could be found for the Minho, but the work group reported a natural sediment export of 0.9–1.85  $\times$  10<sup>5</sup> m<sup>3</sup>/year, reduced to  $0.3-1.2 \times 10^5$  m<sup>3</sup>/year in its present state [5]. Although these numbers, calculated mainly based on empirical studies [13–17], clearly show the dramatic effect of river flow regularization in both fluvial courses, no systematic solid flow monitoring data exist that can confirm if these values are still accurate.

In this context, the quantification and qualification of the present effective sediment exchanges between the NW Portuguese estuaries and the inner continental shelf/coastal zone are crucial to determine the consequent implications of urgent coastal management actions. In order to address this problem, the implementation of pragmatic monitoring solutions and the compilation of previously collected data has become a priority in order to establish the present sediment dynamic regime in this area.

The measurement of suspended sediments and their transport is central to understanding these coastal and estuarine exchanges. Although measurement techniques are continually evolving, it is generally acknowledged that presently available instruments only partially fulfill these requirements. Traditionally, monitoring suspended sediments in aquatic environments involves the collection of water samples from the study site and subsequent laboratory analysis to determine sediment properties. The direct sampling of the mixture of water and sediment is a challenging task, especially during high discharge and rough weather conditions [18,19]. Due to these limitations, Gray and Gartner (2010) documented a 75% decrease in the number of traditional suspended sediment-monitoring stations operated by the United States Geological Survey (USGS) from 1982 to 2008 [20].

The Acoustic Doppler Current Profiler (ADCP) measures currents using the Doppler Effect by transmitting pulses of sound at a constant frequency into the water column. As the sound waves travel, they interact with suspended particles in the moving water that reflect the sound back to the instrument. The instrument then uses the difference between the emitted sound waves and the corresponding echo (Doppler shift) to determine how fast the particles and the water around them are moving. These instruments were originally designed for flow measurement, and, while manufacturers store ADCP acoustic backscatter data for quality checking of the velocity measurements, many researchers have adopted the ADCP backscatter as a surrogate measure of suspended sediments [21]. The basic principles behind suspended particle characterization, using backscatter and attenuation of acoustic signals, are that sound waves passing through a water-sediment mixture will be scattered and attenuated as a function of sediment, fluid, and instrument properties. Therefore, the acoustic metrics of backscatter and sound attenuation relate functionally to sediment characteristics (concentration and size) within an ensonified volume, after adjusting for the influence of fluid and instrument properties [22]. In this context, acoustic backscatter has been used to estimate suspended sediment concentration, and sometimes size, in various environments (see [23–29] for examples).

From the years 2005–2008, Project ECOIS (Estuarine Contributions to Inner Shelf Dynamics) aimed to evaluate the way that the Douro and Minho flow variations induce changes in estuary dynamics and consequently in the sediment transfer rates between the estuaries and the inner continental shelf and coastal zone. During this project, several ADCP datasets were collected in the Douro and Minho estuaries, using multiple reading configurations and covering contrasting seasonal and tidal forcing regimes. Additionally, suspended sediment concentration, salinity, temperature, and turbidity data were collected, allowing for an understanding of how different river flow regimes influence estuarine dynamics. Under the scope of the same project, systematic bottom sediment sampling was carried out in both estuaries in 2005, and a detailed bathymetric survey of the Minho and Douro estuaries was executed in 2006 from the river outlets up to the city of Valença and Crestuma Dam respectively [4,30]. Data collected during project ECOIS have been used by several authors as a starting point to better understand the Minho and Douro's estuarine dynamics [1,4,31-36], and although some knowledge of the Douro's suspended sediment dynamics already existed before 2005 [37,38], little or nothing has been published about the sediment budgets of the Minho before the ECOIS project.

ADCP datasets were collected inside both estuaries with two main objectives in mind. First, acoustic (ADCP) measurements (currents and backscatter intensity) were made of two lower estuary transects, covering different seasonal flow regimes and fortnightly tide forcing, aiming to establish and compare water and sediment fluxes that cross these sections under diverse forcing conditions. Secondly, bottom-moored ADCPs provided a continuous time series of tides (pressure), current, and acoustic backscatter profiles at the lower end of both estuaries planned to extend for periods longer than the two week fortnightly tidal cycle. This paper (Part 1) together with its subsequent paper (hereafter referred as Part 2 [39]), aimed to quantify and qualify (in terms of grain size) the effective sediment exchanges from the Douro and Minho estuaries and the continental shelf, determining the fate and destination of these sediments, based on these ADCP datasets.

In this particular work (Part 1), semi-diurnal tidal cycle water and sediment fluxes between the Douro and Minho lower estuaries and the inner continental shelf were calculated based on transversal ADCP data collected during the summer of 2005 and winter of 2006, under spring and neap tide conditions, complemented with hydro-sedimentological fixed station observations of the water column. In Part 2 of this study, the clustering methods presented by Santos et al. (2021) [40], will be applied to the longer-term bottom-moored ADCPs in an attempt to interpret their acoustic response to the particles within the Minho and Douro estuarine water column, taking into account the contrasting forcing scenarios at the time of the deployments.

The presented results aimed to estimate sediment transfer fluxes at two points inside the lower Minho and Douro estuaries during the surveyed tidal cycles (Part 1), and the general sediment transport patterns at both estuaries' exits under continuously varying river flows and tidal amplitudes (Part 2), based on in-situ measurements. As a final objective, both parts of this study aim to determine the present role of these two estuaries as sources and/or sinks of sediment into the inner shelf and consequently into the coastal zone in an attempt to better understand the dynamic mechanisms conditioning the Douro and Minho estuaries and their implications on coastal management issues.

#### 2. Data and Methods

## 2.1. Study Area

The Minho is an international river that rises at the Serra de Meira, in Spain and reaches the Atlantic Ocean between the cities of Caminha (Portugal) and La Guardia (Spain) after a 340 km course, constituting a natural border between the two countries in its last 70 km. This river plays an important role in hydropower production, tourism, and wine production, and its estuary is considered a reference in ecotoxicological studies and an example for the implementation of water directives in other rivers [1,31,41]. Bathymetric data collected in 2006 revealed a relatively shallow and wide estuary with several sandy banks exposed during low tides, forming small, ephemeral islands (Figure 1) [30]. Near the city of Caminha, the presence of an inlet forming a bathymetric constraint limits an upstream basin where the flow is confined to a narrow and shallow channel [42]. This estuary bottom configuration is not a natural consequence of the river flow on bottom morphology, but the action of successive dredging operations carried out by Portuguese and Spanish authorities in order to maintain the navigability of the lower Minho estuary, namely, in the ferryboat path between Caminha and La Guardia. The Minho estuary is 40 km long, with widths varying between 200 m (upriver) and 2000 m (near the river mouth) [1]. At the mouth itself, the cross-section is narrower ( $\approx$ 300 m) and the estuary outlets into the sea through a NNE-SSW barred trend. Just outside the outlet lies the small granitic island of Ínsua, which has several historical records of being connected to the mainland by a sandy bank (Figure 1) [43]. The estuary presents a semi-diurnal high-mesotidal regime, with the tidal range varying between 2 m (during neap tides) and 4 m (in spring tides), and an average residence time of 1.5 days [44]. Characterization of the tidal signal inside the Minho estuary revealed an asymmetry, with longer ebbs and shorter floods, which increases in significance in the upstream tidal stations, suggesting that it may be a result of the multiple bathymetric restraints [45].

The Minho river flow regime was described in [1]. The river presents an annual average flow around 270 m<sup>3</sup>/s with an important inter-annual variability. Maximum flow rates occur during winter and spring (December–April) and the minimum flow rates during an extended summer period (June–October). In addition to the seasonal behavior, there are important differences between dry and wet years. Average flow values above 4000 m<sup>3</sup>/s were recorded during extreme flow events in 1978, 1979, 2000, and 2001. In this work, the hydrological regime in the Minho estuary was described based on Foz de Mouro hydrometric station records, located about 2 km downstream of Frieira Dam, already in Portuguese territory.

The Douro flows into the Atlantic Ocean through a highly dynamic funnel-shaped narrow estuary (Figure 1). The flow rate at Crestuma Dam is highly dependent on the hydropower production schedule, reaching values over 13,000 m<sup>3</sup>/s [46]. The seasonal river flow regime presents a normal behavior for its latitude, with minimum values in summer and maximum values in winter, related to the natural seasonal variability [47]. However, there is also an important inter-annual variability in the freshwater flow, with large differences between dry and rainy years [1,33,48]. The Douro estuary presents an irregular bathymetry where depths are generally under 10 m, but can reach up to 28 m in narrower sections, outer bends, and former sites of sediment extraction. The southern margin of the estuary mouth includes the São Paio Bay, a wetland and Nature Reserve, and Cabedelo, a dynamic sand spit made up of fluvial and maritime sediments that partially constrains the entrance of marine water (Figure 1).

Both the Douro and Minho Hydrographic Regions [49] are classified according to Köppen's regional climate classification as "dry-summer subtropical" climate (Csb) or often referred to as "Mediterranean" [13,14,50].



**Figure 1.** Location and summary of observations in the Minho and Douro estuaries, superimposed on the bathymetry data collected during ECOIS surveys [30].

## 2.2. Data Collection and Processing

Under the scope of ECOIS, two hydro-sedimentological field surveys were carried out under contrasting seasonal forcing scenarios during expected low river runoff summer (2005) and high river runoff winter (2006) conditions. In brief, collected data consisted of:

- Current and hydrological water column profile observations at a fixed station, covering
  a semi-diurnal tidal cycle (both spring and neaps) and complemented with water
  sampling for suspended sediment assessment;
- Acoustic measurements (currents and backscatter intensity) of two lower estuary transects during the same semi-diurnal spring and neap tidal cycle using acoustic profilers (ADCP);
- Bottom-moored ADCPs providing continuous time series of tides (pressure sensors) and current and acoustic backscatter profiles planned to extend for periods longer than the two week fortnightly tidal cycle (discussed in Part 2).

Figure 1 summarizes the observation positions in both estuaries, which were approximately the same for both surveys.

Hydrological water column tidal variability inside both estuaries was assessed in two fixed stations (StnFix) located in the lower estuaries (Figure 1). At these positions, the water column was profiled at hourly intervals using an Aanderaa RCM9 current meter equipped with conductivity, temperature, and turbidity sensors. The instrument was lowered in 1 to 2 m steps and measurements were taken during 5 min at each vertical step. Water samples were collected near the surface and near the bottom in order to determine suspended sediment concentrations (SSC). Fixed station observations were conducted during 30-h

periods (two semi-diurnal tidal cycles) in spring and neap conditions in the summer of 2005 and in 15-h periods during spring and neap tide conditions in the winter of 2006.

Water samples were filtered using pre-weighed 0.45  $\mu$ m cellulose acetate membranes and analyzed for SSC. Grain size (using a Malvern Master Sizer  $\mu$ P cell) and mineralogical content analyses using X-ray diffraction were performed in selected samples (see [34,35] and Section 3.1 for results). RCM9 turbidity readings in both estuaries revealed a good correlation with SSC, showing that turbidity is a good proxy of suspended matter concentrations in the entire water column [36,51].

During both 2005 and 2006 surveys, the lower Minho and Douro estuaries were transversely surveyed using acoustic Doppler current profilers (ADCP's). These measurements were conducted in both estuaries over a period of approximately one semi-diurnal tidal cycle under spring and neap tide conditions using a bottom-mounted ADCP coupled with a bottom tracking module on a Zebro dinghy (see planned transverse section positions in Figure 1). Two sections were surveyed hourly in the Minho and Douro estuaries: one crossing the fixed station position (*StnFix*) and one representative of the lower end/outlet of both estuaries (*Barra*). Two different ADCP frequency systems were used for the Minho (1200 kHz) and Douro (600 kHz). The 1200 kHz frequency system allows for a better vertical resolution but with a shorter depth range, best suited for the Minho shallow estuary and allowing a vertical resolution of 0.25 m (bin size). The 600 kHz system allows the coverage of the deeper lower Douro estuary, which in some cases can exceed 20 m, with a lower vertical resolution of 0.5 m (bin size).

When it was operationally possible, the transverse observations using the ADCPs were carried out simultaneously with the fixed station hydro-sedimentological observations. Although this was possible for the summer of 2005 surveys and for the Minho in the winter of 2006, in the Douro estuary in 2006, the unavailability of a survey boat only allowed fixed station observations to be carried out during the night and security issues obliged the ADCP surveys to be carried out during daylight. The ADCP survey intervals were then adjusted during neap tide observations in order to allow a four-hour overlap between ADCP transects and suspended sediment sampling in the Douro estuary (see Appendix A).

ADCP transect positioning was carried out manually during both surveys at the start point of each transect. Although start and ends for each transect passing were planned ahead, operational conditions such as river currents and wind did not allow the dinghy to travel in a straight line and, consequently, the actual observed estuary section varied for each passage. X, Y coordinates for each ADCP ensemble (horizontal measuring cell) in each transect were determined from the ADCP's bottom tracking data (boat course and distance travelled), taking into account the known coordinates of the start point. Transects were processed assuming a north-to-south orientation and those collected from south to north were inverted in post-processing. Velocity magnitudes were considered positive upstream and negative downstream (leaving the estuarine system).

Water and sediment fluxes were calculated for each transect depth cell, taking into account the velocity components, acoustic backscatter intensity converted into sediment concentration (see Section 2.3), and the area of each depth cell given by the product of the projected travelled distance and the bin size (vertical measuring cell) taken from ADCP data. Due to the fact that the dinghy's trajectory was not the same for each transect passage, different transect passages yielded different surveyed areas and, therefore, calculated water and sediment fluxes for each one of the surveyed transects were normalized considering the average covered area for each of the considered transect and survey.

#### 2.3. Tidal Cycle Water and Sediment Fluxes

In this work, the general approach described by Wall et al. (2006) [52] and Gartner (2004) [23] was chosen to compute sediment exchanges between the lower Minho and Douro estuaries and the inner-continental shelf for the surveyed tidal cycles.

The method of estimating mass concentration of suspended sediments ( $SSC_{EST}$ ) from acoustic backscatter employs a formula based on the sonar equation for sound scattering

(reverberation) for small particles [23]. In its simplified form, the sonar equation can be written as [53]:

$$RL = SL + TS - 2TL \tag{1}$$

where RL is the reverberation level, i.e., the acoustic response registered by the ADCP, which is dependent on the source level (SL) or intensity of emitted signal, the target strength (TS), i.e., the backscattering strength of the ensonified particles, and on the two-way transmission loss (2TL), which includes sound attenuation due to geometrical spreading, water, and suspended particles integrated along the sound path to the range point. Detailed information about each one of these terms can be consulted in a number of references ([23,25,54,55], among many others).

In Equation (1), both the TS and 2TL terms are dependent on both the suspended sediment concentration as well as on its particle size distribution (PSD). The latter, in the case of the ECOIS datasets, and although some limited information is available, is assumed to be unknown. Therefore, in order to convert the ADCP acoustic backscatter output to estimated concentrations using a single-frequency system, some assumptions and simplifications regarding particle size have to be made [54].

Regarding the sound attenuation term (2TL) and, in the case of this work, SSC values reported in both estuaries were low for both considered seasonal scenarios (in the order of 0.005–0.04 kg/m<sup>3</sup> [30,36], Section 3). Gartner (2004) stated that, for 1200 and 600 kHzfrequency systems, the combination of the scattering and viscous loss terms of sediment sound attenuation [56] account for little attenuation when compared with fluid absorption, unless the particle size is very small or concentrations are very high, neither of which were reported in ECOIS observations [23]. Additionally, and corroborating this statement, the results presented by Santos et al. (2020) showed that sound attenuation due to generally coarse suspended particles in the Portuguese coastal zone was two orders of magnitude lower than the sound attenuation due to the surrounding fluid, for concentration ranges in the same order as the ones measured in both estuaries [54]. Given these results, the attenuation of sound by sediment can be considered negligible, removing PSD dependence on the 2TL term in the equation. As far as the target strength (TS) term is concerned, a known simplification that a single particle size is present throughout the acoustic beam has to be assumed, which will allow the further simplification of this relation, removing the dependency on PSD.

Taking these assumptions into consideration, the method of estimating mass concentration of suspended sediments (SSC<sub>EST</sub>) from acoustic backscatter employs an exponential form of Equation (1):

$$SSC_{EST} = 10^{(A + B \times FCB)}$$
(2)

$$SSC = B \times FCB + A \tag{3}$$

The exponent in Equation (2) contains a term for the measured acoustic backscatter, corrected for geometric spreading and sound absorption by water (FCB—fluid corrected backscatter). The slope (B) and intercept (A) coefficients of the equivalent linear relation in Equation (3) (calibration parameters) can be estimated by fitting the logarithmic values of known concentration values to the corrected acoustic signal (FCB) [23,54]. To this end, SSC values determined at the fixed station in each estuary were depth averaged for each sampling period (hour) and interpolated in order to obtain values representative of the time of the passing of the ADCP in the fixed station transect, following the method described by Wall et al. (2006) [52]. In a second step, EI (echo intensity in counts) was converted to dB and corrected for fluid sound absorption and geometrical spreading, yielding values of fluid-corrected backscatter (FCB) [57]. Estimated values of suspended sediment concentrations could then be calculated from FCB by determining A and B as the intercept and the slope obtained by regression between the ADCP's FCB and the time interpolated values of SSC at the fixed station. Using these datasets, linear regression equations were derived for each estuary and survey according to Equation (3).

Determined regression coefficients (R<sup>2</sup>) were in the order of 20–60% with higher significance (p-values < 10%) in the Douro estuary in 2005 and the Minho in 2006 when the valid calibration points were greater than 10 (Table 1). For similar attempts of converting ADCP backscatter into SSC, Wall et al. (2006) reported  $R^2 = 86\%$  (using a point-integrated water sampler), Gartner (2004) reported R<sup>2</sup> values ranging from 23-85% by crossing ADCP backscatter with a calibrated OBS output, and Santos et al. (2020) reported  $R^2$  ranging from 30–60% for ADCP FCB/LISST concentration output [23,52,54]. Although R<sup>2</sup> values reported in this study were in the same order of magnitude as these published studies, it is acknowledged that the regression significance (*p*-value) fell short of a desirable value. This is due to the fact that suspended sediment samples were collected at the fixed station with a different purpose in mind (namely, the calibration of the RCM9 turbidity sensor), restricting the SSC values available for ADCP calibration to short periods of simultaneous measurements, and to only one of the covered estuarine transect. However, given the scarcity or even absence of similar data in these estuaries, and in order to validate a methodology that can (and should) be improved in future studies, these calibration parameters were accepted, taking their limitations into due consideration.

**Table 1.** Calibration parameters for the linear regression equations between FCB and SSC found for both estuaries.

	В	Α	#Points	<b>R</b> <sup>2</sup>	<i>p</i> -Value
Minho 2005	0.027	-4.503	9	0.212	0.212
Douro 2005	0.030	-4.943	13	0.408	0.019
Minho 2006	0.010	-3.048	11	0.311	0.075
Douro 2006	0.018	-3.539	5	0.587	0.131

## 3. Results

#### 3.1. Estuarine Sediments

Bottom sediment coverage of both estuaries was assessed during project ECOIS and reported in detail by Balsinha et al. (2009) [4] and summarized in Figure 2 and Table 2. These authors divided the Minho estuary into two distinct sectors: the upper estuary, composed mainly of gravelly sand, and a sand-dominated lower estuary where deposit heterogeneity was observed near the mouth of the Coura river (gravelly sand and muddy sand). In the Douro estuary, a greater heterogeneity of deposits was defined. The upper estuary has a coarse nature and is mainly composed of sandy gravel. The middle estuary is characterized by wide variety of deposits, composed by sediments richer in fine material and in the lower estuary the sediments are essentially coarse and composed by small patches of gravel, sandy gravel, gravelly sand, and muddy gravel in the deeper areas.

		>63 µm %	<63 μm %	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	Mean (mm)	σ	D50 (mm)
Minho	Upper	92.4	7.6	20.0	72.4	6.7	0.8	0.73	0.34	0.61
	Lower	99.1	0.9	3.4	95.6	0.9	0.0	0.53	0.57	0.53
Douro	Upper	98.3	1.7	49.5	48.8	1.6	0.2	2.06	0.33	2.09
	Middle	78.8	21.2	33.4	45.4	19.2	2	0.60	0.20	0.75
	Lower	90.85	9.15	50.8	40.1	8.3	0.8	1.38	0.26	1.64

**Table 2.** Average grain size analysis parameters for the Douro and Minho estuarine bottom sediments, divided by sectors, according to the results presented by Balsinha et al. (2009) [4,30].

As far as suspended sediments are concerned, samples collected at the fixed station position revealed low concentrations values for all ECOIS surveyed periods. Lower values were registered during the summer of 2005 survey at both estuaries with values that never went over  $0.01 \text{ kg/m}^3$ , while during the winter surveys maxima were in the order

of 0.02–0.04 kg/m<sup>3</sup> in the Douro estuary and  $\approx 0.02$  kg/m<sup>3</sup> in the Minho. These are in the same order of magnitude as the values reported for the Tamar (Cornwall, UK) and Scheldt (Belgium) estuaries, but one to two orders of magnitude lower than values reported for the San Francisco Bay (USA) and Yangtze (China) [23,58–60]. Suspended sediment concentrations (SSC) variation with depth was highly variable throughout the surveyed tidal cycles, with maxima generally associated with near-bottom levels (see results Section 3).

Suspended sediment grain size analyses yielded modes that ranged from 0.01–0.02 mm (very fine to medium silt) in both estuaries; however, the laboratory protocol on these analyses involved both the chemical digestion of organic matter and the use of anti-flocculation agents. In estuarine environments, like the ones studied in this work, flocculation of clay material and organic matter transported by the river course in the presence of higher salinity values and turbulence is a key phenomenon conditioning the hydrodynamic behavior of the particles in the water column. A floc or aggregate may constitute an order of  $10^6$  individual particles and floc size can range over four orders of magnitude within any one floc population, from clay particles of 1 µm diameter to macroflocs of several millimeters [61,62]. Inside both the Minho and Douro estuaries, X-Ray diffraction revealed a general mineralogical composition of mostly illite and kaolinite with high organic matter content [34], so it is very likely that the grain size actually in suspension inside the estuaries might in fact be much larger than the reported 0.01–0.02 mm, although, intrinsically, it is still fine material (Figure 2 and Table 3).



**Figure 2.** Grain size distribution curves for bottom and suspended sediment samples collected in the Douro and Minho estuaries during the ECOIS project [4,30,35].

**Table 3.** Average grain size analysis parameters for the Douro and Minho suspended sediment samples, collected at the fixed station during a spring and neap semi-diurnal tidal cycle, in the summer of 2005 and winter of 2006 [30,34,35].

		>63 µm %	<63 μm %	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	Mean (mm)	σ	D50 (mm)
Minho	2005	3.8	96.2	0	3.8	79.2	17.0	0.009	0.36	0.010
	2006	6.2	93.8	0	6.2	787	15.1	0.011	0.33	0.011
Douro	2005	5.0	95.0	0.0	5.0	78.0	17.0	0.010	0.34	0.011
	2006	3.8	96.2	0.0	3.8	80.4	15.9	0.011	0.35	0.011

Figure 3 shows the mean monthly discharge values measured at the upstream limit of both estuaries for the 2004/2005 and 2005/2006 hydrological years, as well as the average mean values for the complete analyzed series. The summer of 2005 (September) survey was carried out in an exceptionally dry hydrological year (annual mean of 184.4 and 222.2 m<sup>3</sup>/s at Foz de Mouro and Crestuma, respectively), and the winter of 2006 (February/March) survey was carried out just before river flow values seemed to recover to slightly above mean values in March and April 2006. However, the remaining 2006/2007 hydrological year was again marked by an overall national drought (annual mean of 233.1 and 265.3 m<sup>3</sup>/s at Foz de Mouro and Crestuma, respectively).



Oct. Nov. Dec. Jan. Feb. Mar. Ap. May Jun. Jul. Aug. Sep.

**Figure 3.** Mean monthly discharges measured at the upper limit of the Douro estuary, Crestuma Dam (1 January 1986 to 31 August 2007) and upper limit of the Minho estuary, Foz de Mouro hydrological station (1973/1974 to 2006/2007), compared with the individually monthly values for 2004/2005 and 2005/2006 ECOIS hydrological years.

### 3.3. Minho

Fixed station data collected in the Minho estuary under both runoff revealed an obvious vertical homogeneity during springs and a stratified density structure during neaps (Figures 4 and 5). At this estuarine position, water column density structure mainly responded to the tidal forcing, even during the winter of 2006 observation period when river flow values reached maxima of  $\approx 800 \text{ m}^3/\text{s}$ . A clear tidal asymmetry was observed in both neap and spring conditions: ebb was longer and less intense than flood, revealing a flood dominated estuary [42]. ADCP transect data confirmed fixed station observations, revealing a vertically homogenous estuary and high transversal variability of the flow, mainly due to the estuary's irregular morphology (Figures 6 and 7). Current values could reach up to 1 m/s during low runoff spring flood maxima and during river runoff reinforced ebbs during the winter. Although current maxima are felt mainly at near surface levels due to bottom friction, no significant shear effect could be inferred from both the fixed station and ADCP transect data.



**Figure 4.** Tidal variation in the Minho fixed station water column during the summer of 2005 ECOIS field surveys during spring and neap tides (19/20 and 26/27 September 2005, respectively), based on fixed station RCM9 readings. Top to bottom: salinity (spring tide (**A**); neap tide (**B**); current direction (spring tide (**C**); neap tide (**D**); current magnitude (spring tide (**E**); neap tide (**F**) and suspended sediment concentration inferred from turbidity (spring tide (**G**); neap tide (**H**); tidal variation measured at the Caminha tidal gauge and Minho river discharge (**Q**) measured at Foz de Mouro hydrometric station (located in Portuguese territory, just downstream of the Frieira Dam).



**Figure 5.** Tidal variation in the Minho fixed station water column during the winter of 2006 ECOIS field surveys during spring and neap tides (2 and 9 March 2006, respectively), based on fixed station RCM9 readings. Top to bottom: salinity (spring tide (**A**); neap tide (**B**); current direction (spring tide (**C**); neap tide (**D**); current magnitude (spring tide (**E**); neap tide (**F**) and suspended sediment concentration inferred from turbidity (spring tide (**G**); neap tide (**H**); tidal variation measured at the Caminha tidal gauge and Minho river discharge (**Q**) measured at Foz de Mouro hydrometric station (located in Portuguese territory, just downstream of the Frieira Dam).

SSC tidal patterns inside the Minho estuary are complex. Fixed station observations during low runoff conditions suggested two different origins of suspended material: during spring tides, maxima were associated with the peak estuarine signature in the water column (less saline waters, associated with low tides); during neaps, SSC maxima occurred during flood current maxima at near-bottom levels, probably due to bottom material remobilization by flood. In the winter of 2006, with river runoff values varying between 200–800 m $^3$ /s, salinity values measured at the fixed station position varied between 0-34 PSU. Under these conditions, SSC maxima are synchronous with intermediate salinities of 6–20 PSU, suggesting that these maxima may correspond to an estuarine turbidity maximum composed mainly of fine/organic fluvial material, which tends to flocculate with the increasing ionic concentrations in brackish waters. This turbidity maximum crosses the fixed station position with a downstream direction at mid-ebb, returning with a lesser expression directed upstream at mid-flood during neaps. ADCP transect data collected during the same period showed that, during spring tides, this higher turbidity water mass, flowing mainly near the surface, crossed the Barra position during ebb and was eventually exported outside the estuary (Figure 7).



**Figure 6.** Tidal variation of the lower Minho Estuary transversal sediment fluxes during spring (left) and neap (right) tide periods (20 and 26 September 2005, respectively), based on ADCP current measurements and acoustic backscatter converted into SSC. (**A**,**E**,**I**,**M**)—Ebb; (**B**,**F**,**J**,**N**)—Low Tide; (**C**,**G**,**K**,**O**)—Flood; (**D**,**H**,**L**,**P**)—High Tide. Fluxes are considered positive when entering (upstream) the estuary and negative when exiting (downstream) the estuary.



**Figure 7.** Tidal variation of the lower Minho Estuary transversal sediment fluxes during spring (left) and neap (right) tide periods (2 and 9 March 2006, respectively), based on ADCP current measurements and acoustic backscatter converted into SSC. (**A**,**E**,**I**,**M**)—Ebb; (**B**,**F**,**J**,**N**)—Low Tide; (**C**,**G**,**K**,**O**)—Flood; (**D**,**H**,**L**,**P**)—High Tide. Fluxes are considered positive when entering (upstream) the estuary and negative when exiting (downstream) the estuary.

## 3.4. Douro

Douro fixed station observations under summer low runoff conditions revealed a vertically homogenous water column during springs and clear density stratification during neaps, significantly intensified for the duration of a Crestuma dam discharge (20:00 on September 24th—Figure 8). During the winter of 2006 survey, river discharges registered at Crestuma were high, reaching values of 700 m<sup>3</sup>/s during spring tide observations, and as high as  $\approx$ 1200 m<sup>3</sup>/s felt just before neap tide observations. In fact, under these high river runoff conditions and during neaps, the Douro estuary water column was completely occupied by fresh water with a short period of oceanic influence observed near the bottom just before high tide (Figure 9).



**Figure 8.** Tidal variation in the Douro fixed station water column during the summer of 2005 ECOIS field surveys during spring and neap tides (17/18 and 23/24 Sept. 2005, respectively), based on fixed station RCM9 readings. Top to bottom: temperature in substitution of a malfunctioning salinity sensor (spring tide (**A**) and salinity (neap tide (**B**); current direction (spring tide (**C**); neap tide (**D**); current magnitude (spring tide (**E**); neap tide (**F**) and suspended sediment concentration inferred from turbidity (spring tide (**G**); neap tide (**H**); tidal variation measured at the Barra tidal gauge and Douro river discharge measured at Crestuma Dam.



**Figure 9.** Tidal variation in the Douro fixed station water column during the winter of 2006 ECOIS field surveys during spring and neap tides (28 February and 7 March 2006, respectively), based on fixed station RCM9 readings. Top to bottom: salinity (spring tide (**A**); neap tide (**B**); current direction (spring tide (**C**); neap tide (**D**); current magnitude (spring tide (**E**); neap tide (**F**) and suspended sediment concentration inferred from turbidity (spring tide (**G**); neap tide (**H**); tidal variation measured at the Barra tidal gauge and Douro river discharge measured at Crestuma Dam.

Flood and ebb current magnitudes were similar under absent river runoff; however, while floods were felt throughout the entire water column, ebbs were felt mainly at nearsurface levels, with some evidence of shear effect. Contrary to what happened in the Minho estuary, the current structure of the lower Douro estuary was significantly affected by river runoff variations, with significant reinforcement of ebb currents and weakening or even annulling of floods.

SSC tidal patterns during the summer of 2005 survey revealed low values throughout both spring and neaps with bottom maxima associated with maximum flood currents during spring tide, and a slight increase in SSC values during neaps, synchronous with a river runoff increase. Similarly to what happens in the Minho estuary, during low or absent runoff, suspended material sources at this point correspond mainly to bottom (fine) material resuspension during floods, and some downstream transport of (fine) fluvial material during ebbs, reinforced with river runoff events. This tentative classification of the suspended material as fine is based on the observations of Balsinha et al. (2009), which state that under these hydrodynamic settings, the currents are not able to transport the coarse material found at the estuary's bottom [4].

During the winter of 2006 survey, two SSC maxima were observed during spring tides: the first one was present throughout the whole water column related with downstream moving estuarine waters, and a second one related with near bottom flood current. During neaps, the whole observation period was marked by high concentration values, indistinctively of the tidal phase, but following the same pattern as the river runoff variation measured at Crestuma. It is clear from these observations that, under these high river runoff conditions, the main source of suspended material in the estuary is the Douro river flow (Figure 9).

ADCP transect data represented in Figures 10 and 11 generally confirm the interpretation of fixed station data for all the observed periods: vertical homogeneity during springs and stratification during neaps, under low or absent runoff conditions, and increased sediment flux values with increasing river runoff in 2006, with values as high as 50 g/s felt near the surface.



**Figure 10.** Tidal variation of the lower Douro Estuary transversal sediment fluxes during spring and neap tide periods (18 and 24 September 2005, respectively), based on ADCP current measurements and acoustic backscatter converted into SSC. (**A**,**E**,**I**,**M**)—Ebb; (**B**,**F**,**J**)—Low Tide; (**C**,**G**,**K**,**N**)—Flood; (**D**,**H**,**L**,**O**)—High Tide. Fluxes are considered positive when entering (upstream) the estuary and negative when exiting (downstream) the estuary.



**Figure 11.** Tidal variation of the lower Douro Estuary transversal sediment fluxes during spring and neap tide periods (28 February and 7 March 2006, respectively), based on ADCP current measurements and acoustic backscatter converted into SSC. (**A**,**E**,**I**,**M**)—Ebb; (**B**,**F**,**J**,**N**)—Low Tide; (**C**,**G**,**K**,**O**)—Flood; (**D**,**H**,**L**,**P**)—High Tide. Fluxes are considered positive when entering (upstream) the estuary and negative when exiting (downstream) the estuary.

## 3.5. Estuary/Inner Shelf Sediment Exchange Patterns

In the Minho estuary, during low runoff conditions, tidal asymmetry resulted in longer ebbs, but lower sediment and water fluxes at both transect positions, which were counterbalanced by the shorter, but more intense, flood upstream fluxes (Figure 12). Tidal amplitude during springs was responsible for sediment flux values that could reach 20 g/s during floods, four-fold the maximum value determined of  $\approx 4$  g/s for similar tidal phases during neaps. Under high runoff conditions and during springs, the reinforced longer ebb fluxes were responsible for sediment fluxes in the same order as floods, with a maximum of pprox15 g/s directed downstream. During neaps, the decreased tidal amplitude was no longer able to counteract the fluvial input, resulting in significant disparity between upstream flood fluxes ( $\approx$ 1–2 g/s for a period of approximately 3 h in the second half of flood) and downstream fluxes that could reach values as high as 15 g/s at mid-ebb at the Barra transect (Figure 12). During this observation period, a significant difference existed between the two transect positions, with the Barra transect presenting values of downstream directed water and sediment fluxes sometimes three-fold those felt at the fixed station position. Although no documented values of runoff could be consulted, it is possible that the fluxes felt at the Barra position during this observation period could be the result of the addition of the River Coura contribution at this point in the estuary. Although the River Coura confluence with the Minho estuary is situated upstream of both transect positions, there seems to be a preferential pathway of this affluent's flow through a channel located at the left (Portuguese) margin of the estuary, which eventually joins the main estuary channel at the Barra position (Figure 1).



**Figure 12.** Water and sediment fluxes measured in the lower Minho estuary at the Barra and StnFix transects during the summer of 2005 and winter of 2006 ECOIS surveys, based on ADCP acoustic backscatter and current measurements.

In the Douro estuary, under low or absent runoff (summer of 2005), sediment flux values were low throughout both neap and spring tide observations. Maxima were associated with flood current maxima (upstream transport), resulting in a general import of water and sediment into the estuary during springs and a close to null exchange during neaps (Figure 13). In the winter of 2006, sediment fluxes were within the same order of magnitude both in neap and spring tides with maxima >15 g/s flowing downstream (Figure 13). These data show the significant influence of the higher and more persistent river flow inside the Douro estuary during neaps. In fact, during this period, the Douro estuary behaved as a river, with water and sediment fluxes directed downstream throughout the tidal cycle, with the exception of mid-flood when the entrance of the tidal wave was able to counteract the effect of the river flow, resulting in a null transport situation in all of the surveyed transects.

Total water and sediment fluxes passing through each transect during the observed tidal cycles are presented in Table 4 (Minho) and Table 5 (Douro). Results showed that these estuaries, under the observed artificialized river flow conditions, can act as both sources and sinks of sediments in the NW Portuguese littoral system.

Under low river-flow conditions and spring tidal amplitudes (summer of 2005), the Minho estuary effectively imports sediment in the order of  $10^4$  kg. Taking into account both the fixed station and ADCP data interpretation, this sediment intake is related to the upstream transport of resuspended coarse bottom material by the flood current [4,32]. During neaps, a sediment export in the order of  $5-10 \times 10^3$  kg was determined at both the fixed station and Barra transects. Under this tidal regime, the slight increase in river discharge values coupled with the decrease of the tidal amplitude allowed for some export

of suspended material into the inner shelf; however, the analyzed data do not allow the inference of the type (size) of exported sediment.

Under winter conditions, Minho river flow values in the order of 500 m<sup>3</sup>/s yielded a completely different transport scenario. During spring tides, an export of approximately  $70 \times 10^3$  kg of sediment could be inferred from the Barra transect data. Barra and fixed station transect data revealed that during this tidal cycle, upstream maxima during flood were counteracted by downstream maxima during ebb, reinforced with the increase of river discharge values during the second half of the observations (Figure 12). During neaps, sediment transport was directed downstream during most of the surveyed tidal cycle with the exception of the second half of flood, when the current near the bottom was able to counteract the river discharge and there was evidence of some near-bottom sediment transport upstream. Export values of  $30 \times 10^3$  kg and  $100 \times 10^3$  kg were computed for the fixed station and Barra transect for this tidal cycle respectively, and, according to transect data, downstream transport at both sites occupied the whole water column (Figure 12 and Table 4).



**Figure 13.** Water and sediment fluxes measured in the lower Douro estuary at the Barra and StnFix transects during the summer of 2005 and winter of 2006 ECOIS surveys, based on ADCP acoustic backscatter and current measurements.

In the lower Douro estuary, evidence of sediment import at the Barra position can be inferred under low discharge and spring and neap tide conditions during the September 2005 survey. Sediment intake was in the order of 10<sup>4</sup> kg during spring tides and one order of magnitude lower during neaps. During these summer conditions, with close to absent discharges from the Crestuma Dam, sediment was transported near bottom levels by the flood current, and the ebbs were not able to transport this material outside the estuary.

		Survey Duration (Hours) (% of Total Tidal Cycle)	Water (×10 <sup>6</sup> m <sup>3</sup> )	Sediments (×10 <sup>3</sup> kg)
20.SEP.2005 SPRING TIDE (12.3 h) 70.1 m <sup>3</sup> /s *	Barra	12 (97%)	2	50
	StnFix	11.9 (97%)	6	7
26.SEP.2005 Neap tide (13.8 h) 113.1 m <sup>3</sup> /s *	Barra	11.8 (85%)	-6	-5
	StnFix	11.8 (85%)	-5	-10
02.MAR.2006 Spring tide (12.5 h) 477.3 m <sup>3</sup> /s *	Barra	11.1 (89%)	-8	-70
	StnFix	12 (96%)	2	-3
09.MAR.2006 Neap tide (12.6 h) 557.4 m <sup>3</sup> /s *	Barra	12.3 (98%)	-20	-100
	StnFix	10.8 (85%)	-4	-30

**Table 4.** Total net water and sediment fluxes crossing the Minho surveyed transects during the observed semi-diurnal spring and neap tidal cycle (summer of 2005 and winter of 2006).

\* mean daily flow measured at Foz de Mouro.

**Table 5.** Total net water and sediment fluxes crossing the Douro surveyed transects during the observed semi-diurnal spring and neap tidal cycle (summer of 2005 and winter of 2006).

		Survey Duration (Hours) (% of Total Tidal Cycle)	Water (×10 <sup>6</sup> m <sup>3</sup> )	Sediments (×10 <sup>3</sup> kg)
18.SEP.2005 SPRING TIDE (12 h)	Barra	11.2 (93%)	10	30
$0 \text{ m}^3/\text{s}^*$	StnFix	11.2 (93%)	5	20
24.SEP.2005 NEAP TIDE (12.2 h) 83.41 m <sup>3</sup> /s *	Barra	11.4 (93%)	2	4
	StnFix	11.4 (93%)	-1	-4
28.FEB.2006 SPRING TIDE (12 b)	Barra	13.4 (111%)	-3	-20
$268.85 \text{ m}^3/\text{s}^*$	StnFix	13.6 (113%)	-8	-60
7.MAR.2006 NEAP TIDE (12.4 h)	Barra	13.9 (112%)	-30	-200
569.25 m <sup>3</sup> /s *	StnFix	13.9 (112%)	-30	-300

\* mean daily flow measured at Crestuma Dam.

During the winter of 2006, average river discharge values of  $\approx 250 \text{ m}^3/\text{s}$  felt during spring tide observations yielded sediment export during all tidal scenarios and transect positions. During neaps, sediment export in the order of  $10^5 \text{ kg}$  was computed at both observed transects. In fact, under these river discharge and low-amplitude tide conditions, the Douro estuary behaved as a river with water and sediment flows directed downstream during most of the tidal cycle (Table 5).

## 4. Discussion and Final Conclusions

According to the presented results, the Minho estuary is characterized by a general vertical homogeneity and high transversal flow variability due to its complex bottom morphology [30–32]. The Minho estuary is as a vertically homogeneous estuary wherein the tidal range is relatively large compared with the water depth and the turbulence produced by the velocity shear on the bottom is enough to mix the water column completely [63]. However, some other scenarios have been observed when the Minho estuary water column can present some density stratification, mainly during neaps and accentuated by river discharge (Figures 5 and 6, neap tides).

The net sediment fluxes calculated for the considered observation periods revealed that, under spring tide/low runoff conditions, the Minho estuary effectively imports sediments from the inner shelf. Fixed station and ADCP data revealed that this material enters the estuary via flood current, mainly at near-bottom levels. When river discharge levels increase ( $\approx 200 \text{ m}^3/\text{s}$ ) and during neaps, the Minho estuary effectively exports sediments into the inner shelf, in the order of  $10^4$  kg of sediments per tidal cycle, mainly at the lower part of the estuary (Barra transect). Fluvial input into the Minho estuary, under these forcing conditions, flows at near surface levels due to density stratification and this river input seemed to be the main source of suspended sediments at this point of the estuary. Although analyzed hydro-sedimentological data do not allow for any inference of the type of sediment that is being exported into the inner shelf, the fact that this material is being transported at surface levels leads us to believe that it is fine in nature.

The Douro estuary is characterized by the presence of a salt-wedge-type structure with marked vertical stratification, especially during neaps [36]. It can be classified as a mesotidal estuary with a partially stratified structure [63]. According to the presented data, the Douro estuary circulation model is in agreement with the previous observations reported by Instituto Hidrográfico and later confirmed by Portela [37,38]. Portela classified the Douro as a system dominated by sand- and gravel-sized sediments wherein the evolution of the bed has basically been dependent on dredging operations for the past 20 years, where sediment transport capacity solely due to tidal currents is very limited. As far as fine sediment dynamics are concerned, Instituto Hidrográfico concluded that suspended sediments are transported by ebb currents in the surface layers of the estuary's water column towards the sea, and are "captured" by the flood currents in deeper levels of the water column, forming a "closed circulation" cell. Although this circulation model might be true for most of the tidal cycles in the Douro estuary, especially when the Crestuma Dam is artificially holding the natural flow of the river into the estuary, data presented in this work revealed that evidence of sediment transport existed when dam discharges were over 500  $\text{m}^3$ /s and during neaps, with calculated sediment export values for the winter of 2006 neap tide observations in the order of  $10^5$  kg per semi-diurnal tidal cycle. When the tidal amplitude was high (spring tide) and there was no significant discharge, there was some sediment import associated with near-bottom flood currents that remobilized bottom material upstream. Laboratory-determined fixed station grain-size signatures of the transported material revealed very fine silts, which did not match the very coarse bottom sediment signature in the lower Douro estuary, showing that this suspended material probably continues moving towards the inner shelf [4].

Integration of ADCP transect current and estimated sediment concentration data allowed for the calculation of water and sediment fluxes that cross the Barra and StnFix sections in both estuaries. Given the low significance of regression results between the ADCP's backscatter and SSC values determined for these survey periods (Table 1), the determined sediment flux values should be interpreted within their order of magnitude and direction of transport (upstream or downstream).

During the winter of 2006 survey, the effective water and sediment exported into the inner shelf by both the Minho and Douro estuary flow can be corroborated by additional data collected in the inner shelf during the same period under the scope of an ECOIS-affiliated project. Both the Douro and Minho flows were related with the presence of a low salinity and high turbidity superficial lens in the inner-shelf water column [34].

Summarizing, under the current artificialized conditions, the Minho and Douro mainly act as sinks of sediment under spring tide conditions (in the order of  $10^4$  kg of sediment per semi-diurnal tidal cycle) when river runoff values are low. During neaps, and when river runoff values are able to counteract the tidal flood, both estuaries act as sources of suspended material (fine sediments) into the inner shelf, in the order of  $10^5$  kg of sediment per semi-diurnal tidal cycle.

According to these results, and when compared with the Minho, the Douro still acts as the major source of sediments exported into the continental shelf. However, the sediments coming out of the estuaries under unexceptional winter river flow conditions and neap tidal amplitudes are most probably fine in nature. According the established sediment dynamics conceptual model, this type (size) of sediment will flow into the continental shelf and eventually be deposited in the mid-shelf muddy deposits [64–66], and will not in any case help the sediment-depleted coastal zone just south of these estuaries.

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Conflicts of Interest: The authors declare no conflict of interest.

## Appendix A

**Table A1.** Dates and intervals of observations inside the Minho and Douro estuaries during the ECOIS 2005 and 2006 field surveys.

	Minho	Douro	
	Fixed Station	Fixed Station	
	Start: 13:00 UTC 19/09/2005	Start: 13:00 UTC 17/09/2005	
2005 Spring Tidos	End: 18:00 UTC 20/09/2005	End: 18:00 UTC 18/09/2005	
2005—Spring fides	ADCP Transects	ADCP Transects	
	Start: 06:00 UTC 20/09/2005	Start: 07:00 UTC 18/09/2005	
	End: 18:00 UTC 20/09/2005	End: 19:00 UTC 18/09/2005	
	Fixed Station	Fixed Station	
	Start: 06:00 UTC 26/09/2005	Start: 05:00 UTC 24/09/2005	
2005 Noon Tidos	End: 11:00 UTC 27/09/2005	End: 09:00 UTC 25/09/2005	
2005—Neap Tides	ADCP Transects	ADCP Transects	
	Start: 07:00 UTC 26/09/2005	Start: 07:00 UTC 24/09/2005	
	End: 19:00 UTC 26/09/2005	End: 19:00 UTC 24/09/2005	
	Fixed Station	Fixed Station	
	Start: 06:00 UTC 02/03/2006	Start: 19:00 UTC 28/02/2006	
2006 Spring Tidos	End: 21:00 UTC 02/03/2006	End: 09:00 UTC 01/03/2006	
2006—Spring fides	ADCP Transects	ADCP Transects	
	Start: 07:00 UTC 02/03/2006	Start: 06:00 UTC 28/02/2006	
	End: 19:00 UTC 02/03/2006	End: 19:00 UTC 28/02/2006	
	Fixed Station	Fixed Station	
	Start: 07:00 UTC 02/03/2006	Start: 18:00 UTC 07/03/2006	
2006 Noon Tidos	End: 21:00 UTC 02/03/2006	End: 09:00 UTC 08/03/2006	
2000—Neap Tides	ADCP Transects	ADCP Transects	
	Start: 07:00 UTC 02/03/2006	Start: 10:00 UTC 08/03/2006	
	End: 19:00 UTC 02/03/2006	End: 24:00 UTC 08/03/2006	

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