Application of Marine Spatial Planning tools for tidal stream farm micro-siting

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Abstract

The operation of tidal stream energy farms may interfere with other uses of the marine space, especially in depth-limited areas (estuaries, rivers, etc.) which are typically subject to multiple demands of use. The Marine Spatial Planning Directive (MSP) was passed by the European Commission in 2014 to ensure a harmonic coexistence between different maritime activities and to protect the marine environment. In this context, the objective of this work is to present a methodology based on MSP tools for tidal-farm siting in depth-limited areas. The methodology is illustrated through a case study: Ria de Ribadeo, a shallow-water estuary in NW Spain. Having considered a number of uses (archaeological, biodiversity, fishing, aquaculture, recreational and navigation), two exploitable tidal farm sites (Areas A and C) with annual energy densities of 1 $GWhm^{-2}$ were found. The estuary is periodically dredged to maintain navigation. Dredging-related risks were analysed using a novel indicator, the Dredging Associated Risk (DAR), based on which Area C was discarded and Area A had its exploitable surface area reduced by 25%. In sum, the methodology proposed was proven to be effective for tidal stream farm planning.

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1. Introduction

With the aim of mitigating climate change and reducing fossil fuel dependence, from the beginning of the 21^{st} century, different policies have been developed, initiating a transition towards a non-polluting and sustainable energy model. Examples of those policies are: (i) the Paris Agreement (United Nations) [1], (ii) the 2030 Agenda for Sustainable Development (United Nations) [2] and (iii) the EU 2030 Framework for Climate and Energy (European Union) [3]. The latter aims to increase the share of renewables up to 32% of the EU's energy consumption and, cutting Greenhouse Gas (GHG) emissions by 40% compared to 1990 levels [4]. In this context, Marine Renewable Energy (MRE), which presents an abundant and geographically-diverse resource (up to 32 TW) [5], is expected to play an important role to achieve the aforementioned goals. For this purpose, in 2015 the EU Commission created the Ocean Energy Forum, with the objective of developing strategic road-maps for the development of a MRE industry. Consequently, a year later, the road-map *Building ocean energy for Europe* was released [6], identifying that: (i) MRE could supply up to 10% of EU's energy demand by 2050, (ii) diversification of the EU's low-carbon generation capacity is required to achieve the goals in terms of GHG emissions; (iii) MRE exploitation may reduce significantly GHG emissions (up to 276 $Mt\ CO_2e$ annually) by 2050, and (iv) MRE represents a fantastic opportunity to develop a new industrial sector, boosting EU's economy and contributing to the long-term sustainability of its coastal regions.

Within the large variety of MRE sources, tidal stream energy, with an estimated global resource of 120 GW [7], stands out. Tidal stream energy is characteristic of coastal regions, where tidal height variations combine with the morphological conditions, to produce tidal currents [8]. Consequently, the kinetic energy stored in the tidal currents is used for electricity generation, by means of Tidal Energy Converters (TECs), which are placed directly into the flow [9]. In this context, the main advantages of tidal stream energy are: (i) renewable nature and high predictability of the resource [10] (ii) high load factors associated to tidal currents [11] and (iii) non-existence of extreme flows that could jeopardise the long-term survivability of submerged TECs (i.e. tidal streams velocities rarely exceed 6 ms^{-1}) [11]. Despite all these facts, tidal stream energy is far from being commercially viable for large-scale electricity generation [12]. On these grounds, the following facts stand out: (i) despite recent breakthroughs (MeyGen tidal energy project [13]), TEC technology is not yet mature, (ii) few locations around the world meet the requirements in terms of tidal flow velocities (> 2 ms^{-1}) and water depths (> 25 m) for the operation of the first and second generation of TEC concepts [14], (iii) TEC operation usually takes place in harsh marine environments, which increases significantly the difficulty and costs of installation and maintenance operations [12], (iv) operation of TECs may cause significant disruptions of different marine environmental processes such as transient and residual circulation patterns [15], transport of suspended matter (e.g. pollutants [16], nutrients [17] and sediments [18]) and ambient turbulence conditions [19], and last but not least (v) potential interactions with other marine uses such as navigation [20], fishing, aquaculture [21] and recreational activities [22].

The latter highlights the necessity of managing the different maritime uses and activities (MRE, fishing, aquaculture, recreational and others) using a holistic approach. For this purpose, in 2014 the EU released the 2014/89/EU Directive on Maritime Spatial Planning (MSPD) [23], whose main objectives are: (i) reduce conflicts and create synergies between different maritime uses [24], (ii) set a clear and predictable legal framework to attract investments in maritime activities [25, 26], (iii) increase cross-border cooperation between EU Member States [27] and (iv) ensure the protection of the marine environment by identifying impacts and opportunities for multiple maritime uses. Consequently, EU Member States had to transpose Directive 2014/89/EU into their national law by 2016 and define their respective Maritime Spatial Plans (MSPs) by 2021. Regarding MRE exploitation, MSPD offers the opportunity to improve and harmonise the legal framework for licensing MRE projects, increase legal security for MRE stakeholders and, reduce and arbitrate conflicts with other maritime users [28].

For the specific case of Spain, Royal Decree 363/2017 [29] transposes Directive 2014/89/EU into the Spanish national law. RD 363/2017, in its general provisions and article 10, includes the exploitation of MRE within the different maritime uses to be considered for the elaboration of future MSPs. For each of the Spanish marine demarcations, MSPs are still under development (currently in the public consultation stage) and they are expected to come into force by the end of 2021 or early 2022. MSPs will follow a hybrid planning approach with the aim of ensuring a seamless coexistence between maritime uses and activities, while ensuring a Good Environmental Status (GES). For this purpose, MSPs identify the so-called *priority use areas*, for which a set of rules and provisions are defined to avoid that the main use of the area is not compromised by other marine activities. In consequence, proposals for other marine activities must demonstrate compatibility with the priority use of the marine area. On these grounds, planning the installation of tidal farms will require a detailed (i) spatial identification of different maritime uses and (ii) assessment of the potential impacts caused by other marine activities on the operating conditions of tidal farms, and *vice versa*; with the purpose of ensuring an harmonic coexistence among the different maritime uses of the area of interest. As a result, Marine Spatial Planning will contribute to decrease the level of uncertainty of tidal energy projects, decreasing interactions with other marine activities and enhancing legal certainty [28]. Further details on the Spanish maritime legislation can be found in Section 2.

The technological development of TECs, has brought the opportunity of exploiting the tidal stream energy resource in a wider variety of coastal locations, especially at shallow tidally-driven estuaries and rivers [30], which also host of multitude of marine uses (shipping, fishing, aquaculture and recreational activities). Moreover, the tidal stream resource at depth-limited regions is highly sensitive to natural (sediment transport) and/or anthropogenic (dredging of navigation channels) bathymetric changes [31]. Consequently, the holistic approach of Marine Spatial Planning appears as an excellent tool for tidal farm siting, especially in those regions. Previous research has dealt in detail with the optimum siting of tidal stream energy farms, considering different constraints such as available resource [14], maintenance [32], operating costs [33], power production [34], layout optimisation [35], environmental impact [36] and economic viability [37]; however, few works have applied Marine Spatial Planning in depth to find the optimum location for tidal farms [38, 39, 40].

Against the foregoing backdrop, the objective of this paper is to present a methodology based on Marine Spatial Planning with the aim of finding the most suitable location for the installation of tidal farms in depth-limited regions, using for this purpose Ria de Ribadeo (Figure 1), a shallow and highly energetic estuary located in NW Spain [41], as case study. The remainder of this paper is structured as follows: Section 2 presents the main characteristics of the Spanish legal framework for maritime activities. Section 3 describes in the detail the maritime uses and characteristics of Ria de Ribadeo. Section 4 presents the Dredging Associated Risk (DAR) indicator for depth-limited tidal sites. Section 5 illustrates the application of Marine Spatial Planning for tidal farm siting in Ria de Ribadeo. Finally, conclusions are drawn in Section 6.

2. Spanish Maritime Legal Framework

Spain, as any other EU Member State, legislates the protection of marine environment and management of maritime activities, according to: (i) Directive 92/43/EEC on nature conservation [42], (ii) Marine Strategy Framework Directive 2008/56/EC (MSFD) [43] and (iii) Maritime Spatial Planning Directive 2014/89/EU (MSPD) [23].

In May 1992, the European Council approved Directive 92/43/EEC on the conservation of natural habitats and wild fauna and flora, establishing the EU Natura 2000 ecological network of protected areas (Sites of Community Importance, SICs), preserving them against potentially damaging developments. EU Commission Decisions 2004/813/EC [44] and 2006/613/EC [45] define the SICs for the Atlantic and Mediterranean biogeographical regions of Spain, respectively. In this context, Law 42/2007 [46], which transposes Directive 92/43/EEC into the Spanish domestic law, establishes in its article 42.3 that Spanish autonomous regions have a period of six years to declare the SICs, which belong to their jurisdiction area, as Special Areas of Conservation (SAC) and/or Special Protection Areas for Birds (SPAB) and to elaborate managing and monitoring plans for those areas.

In June 2008, the European Parliament approved the Marine Strategy Framework Directive 2008/56/EC (MSFD) [43], which aims to preserve the marine environment and to ensure its long-term sustainable use. MSFD was transposed into the Spanish national law in December 2010, by means of Law 41/2010 [47], whose main goal is to achieve GES in the marine environment. To this end, specific strategies for each Spanish marine demarcation were developed, proposing coherent planning of activities and uses of the marine environment compatible with the preservation of its biodiversity. Marine strategies are subject to be revisited every six years. In addition, Law 41/2010 creates the Network of Marine Protected Areas (NMPAs), setting the mechanisms for their designation, preservation, environmental monitoring and management of marine activities. Examples of MPAs are areas belonging to Natura 2000 network (SICs, SPAs and SPABs), World Heritage and Biosphere Reserve UNESCO areas [48] and Ramsar [49] and OSPAR [50] sites.

RD 363/2017 [29], of April 2017 transposes Maritime Spatial Planning Directive 2014/89/EU (MSPD) into the Spanish law, establishing the legal framework for the management of marine spaces. For this purpose, RD 363/2017 contemplates the elaboration of Marine Spatial Plans (MSPs) for each of the Spanish marine demarcations, with the aim of ensuring a sustainable development and harmonic coexistence of marine sectors and protection of the marine environment. For this purpose, RD 363/2017 establishes the guidelines for the elaboration and revision of MSPs. However, it does not establish either priority criteria for the execution of maritime activities or rules to arbitrate conflicts between different maritime users [28]. Regarding the exploitation of Marine Renewable Energy (MRE), RD 363/2017 highlights in Article 5.c the need of producing energy from MRE sources to foment a sustainable development of coastal regions, while Article 10.2 includes MRE exploitation among the maritime activities to be considered for the elaboration of MSPs. As aforementioned, MSPs, which are currently under public consultation, are expected to come into force by the end of 2021 or early 2022, and will be susceptible to revision, every ten years. Overall, MSPs will follow a hybrid planning approach, prioritising the coexistence of multiple marine activities in the same marine space, as well as ensuring its GES. Nonetheless, *priority use areas* will be defined and, therefore, proposals for other marine activities must demonstrate compatibility with the designated use of the area. It is worth noting that protected marine areas are classified by the MSPs as priority use areas for the preservation of biodiversity and will be regulated according to the legislation applicable to them. Finally, *high-potential areas* will be also identified, giving priority to uses and activities, which present a high-future development [51].

Additionally, RD 1028/2007 [52] regulates the licensing process of MRE installations in the Spanish jurisdictional waters. RD 1028/2007 contemplates the commercial licensing only for off-shore wind farms, while for other types of MRE it establishes a simplified licensing procedure for experimental installations. RD 1028/2007 also classifies the Spanish littoral in appropriate and non-appropriate areas for the installation of off-shore wind farms, based on an environmental impact assessment carried out by the inter-ministerial commission of Marine Environment, Industry and Tourism. On these grounds, it is expected that MRE exploitation areas proposed by RD 1028/2007 will be overruled by future MSPs [53]. Furthermore, future regulatory changes are expected to streamline licensing procedures of MRE plants [53, 54]. Finally, Figure 2 shows the linkages among the different legislation presented in this section.

3. Characterisation of maritime exclusive areas for Ria de Ribadeo

Ria de Ribadeo is a shallow coastal embayment, with a total surface area of approximately 10 km^2, located in NW Spain (Figure 1). Its location, naturally sheltered from the harsh marine environment of the Bay of Biscay, has prompted a significant development of different maritime uses such as aquaculture, tourism and recreational activities. Ria de Ribadeo also acts as a natural border between the autonomous regions of Galicia and Asturias (Figure 1), housing a multitude of commercial and trading activities throughout the ports of Ribadeo and Figueras (Figure 1). In addition, Ria de Ribadeo presents remarkable biodiversity and archaeological heritage [49]. Finally, Ria de Ribadeo has an abundant tidal stream energy resource [41], with three potential tidal sites identified at the middle *ria* [31], whose exploitation could bring a fantastic opportunity for the development of a new industrial sector in the region.

However, the exploitation of the tidal resource could interfere with the particular marine environment [56] and biodiversity of the *ria* [57] and with other relevant socio-economic activities such as aquaculture and marine navigation [58]. Moreover, periodic dredging operations of the approach channels of Ports of Ribadeo and Figueras alter the hydrodynamic patterns of the *ria* [31]. Consequently, the available resource and operating conditions of tidal farms could be drastically modified, jeopardising their long-term viability [31]. In this context, before planning the installation of a tidal farm in Ria de Ribadeo a holistic approach is necessary, considering the potential interactions of tidal farm operation with the maritime uses of the *ria*, which are described in detail from Sections 3.1 to 3.6, using for their definition, GIS spatial analysis (Figures 3 to 5).

3.1. Special Areas of Conservation (SAC) and Special Protection Areas for Birds (SPAB)

Decision 2004/813/EC identified Ria de Ribadeo as a Site of Community Importance (SIC) within the Atlantic biogeographical region [59]. As mentioned in Section 2, Law 42/2007 establishes that the Spanish autonomous regions should classify SICs, lying inside their jurisdiction areas, as SACs and/or SPABs. Therefore, the parliament of Galicia approved Decree 37/2014 [60], which identified 59 SACs and 16 SPABs, and also proposes managing and monitoring plans for those areas. In this context, Ria de Ribadeo was classified as SPAB (ref. ES0000085 [61]), and as SAC (ref. ES11200002 [60]) within the estuary/wetland category. As a result, Ria de Ribadeo is included in the Spanish Network of Marine Protected Areas (NMPAs) [62]. Decree 37/2014 classifies both SACs and SPABs into three different categories: (i) protected areas, in which only traditional activities with little to no impact on ecosystems are allowed, (ii) conservation areas, where traditional and non-traditional activities compatible with the local ecosystems could be carried out and (iii) general use areas, in which industrial activities may be allowed after a detailed environmental impact assessment.

Figure 3 shows the spatial distribution of the aforementioned areas across Ria de Ribadeo. It can be observed that in the mouth of River Eo, there is a protected area, which covers a surface of 160 *ha*. The inner and outer sections of the *ria* are marked as conservation areas, spanning a total surface of 392 *ha*. Conversely, the middle section of the *ria* (80 *ha*) is declared as a general use area. Furthermore, it is worth noting, that RD 363/2017 and, consequently, MSPD applies only for the outer section of the *ria*, since their inner and middle sections lie in the category of transitional waters (Figure 3). In this context, the draft version of the MSP for the North-Atlantic Spanish demarcation classifies the outer section of Ria de Ribadeo as a priority use area for the preservation of biodiversity [55], highlighting Decree 37/2014 as the applicable legislation to manage maritime activities. All in all, and despite the inner and middle sections of the *Ria de Ribadeo* lie outside the scope of RD 363/2017, the tools provided by MSP are still very valuable to find the optimum location of tidal farms in the area of study.

3.2. Archaeological protected sites

Ria de Ribadeo presents an outstanding archaeological heritage. A multitude of archaeological remains, from centuries XVI to XVIII belonging to merchant and war ships, have been found in the outer and middle sections of the *ria* (Figure 4). Considering the large number of documented shipwrecks in the *ria*, further archaeological wrecks are expected to remain undiscovered, especially in the surroundings of the marina harbour, which coincides with the historical location of the port. Table 1 summarises the main characteristics and archaeological value of the wrecks found in the *ria*.

In this context, Law 5/2016 [63], which regulates the cultural heritage of the autonomous region of Galicia, establishes protection areas of 200 *m* radius for archaeological sites, where any seabed action is prohibited. Figure 4 shows the different archaeological protected areas of Ribadeo, which are mainly concentrated around the marina harbour with two additional areas located at both sides of the *ria* mouth, spanning a total surface 32.64 *ha* (Table 2). Consequently, the installation of tidal farms in those areas is discarded beforehand, since its operation could disrupt seabed morphology, jeopardising the integrity of archaeological wrecks.

3.3. Biodiversity protected sites

Ria de Ribadeo behaves as a positive, partially mixed estuary with a two-layer estuarine circulation pattern [64], which derives from the complex interaction of tides, fresh water run-offs and wind conditions. In addition, from the months of April to October, Ria de Ribadeo experiences coastal upwelling events caused by northerly shelf winds. As a result, oceanic water (Eastern North Atlantic Central Water), which is cold and nutrient-rich, enters the *ria* [65]. The combination of those coastal processes explains the high biological productivity of Ria de Ribadeo [66]. In this context, an abundant population of macro-algae species such as *pelvetia canaliculata* and *ulva* is present in the inter-tidal areas of the middle section of the *ria* (Figure 5). Additional algae species such as *ascophyllum nodosum*, *fucus ceranoides*, *fucus espirabis*, *fucus vesiculosus*, *gracilaria verrucosa* and *mastocarpus stellatus* can also be found in the *ria* [67]. Therefore, in order to preserve this marine ecosystem, the macro-algae sites (Figure 5) are catalogued as exclusion zones for other maritime activities, covering a surface of 290 *ha* (Table 2)

3.4. Fishing and aquaculture sites

As mentioned in the previous section, Ria de Ribadeo stands out for its marine biodiversity, laying the foundation for a strong fishing and aquaculture industry. On the one hand, the fishing grounds are mainly located in the *ria* mouth (Figure 5). On the other hand, shell-fishing gathering (bivalve molluscs and octopuses) represents an important maritime activity both in the middle and inner sections of the *ria* (Figure 3). Finally, in recent years, the farming of oysters on floating-wooden platforms is increasing significantly, requiring a significant amount of space, especially at the inner *ria* (Figure 5). Again, in order to avoid potential disruptions to fishing and aquaculture activities, the aforementioned sites are excluded from additional marine uses.

3.5. Touristic sites

Touristic and recreational activities are an important source of employment and income generation for the region. In this context, Law 2/2013, which regulates the protection and sustainable use of coastal areas, establishes in its article 69 that bathing or beach areas should cover at least a strip of 200 *m* width parallel to the coast, in which any other activity is prohibited for safety reasons. For the rest of the coast, an exclusive public domain area of 50 *m* width is defined. Finally, Figure 5 shows the spatial distribution of public domain and beach areas in the *ria*, which span 155 *ha* and 31.3 *ha*, respectively.

3.6. Marine navigation areas

The privileged location of Ria de Ribadeo (Figure 1) makes ports of Figueras and, especially, Ribadeo relevant trading ports at a regional level. Consequently, ensuring adequate operating conditions for both ports becomes essential. For this purpose, any disruption in the approach channels of both ports must be avoided. The main navigation channel of the *ria* is located on its left side (Figure 5), with a total width of 90 m and a draught of 5 m relative to the Lowest Astronomical Tide (LAT). A branch of the main channel, whose main dimensions are 50 m wide and 3 m draught, gives access to the port of Figueras (Figure 5). As a result, both channels cover a total surface of 28.4 ha.

However, the complex circulation pattern present in the *ria* [64], drives a significant sediment transport towards its middle section, causing significant sedimentation in the approach channels of Ribadeo and Figueras ports. To ensure operativity of both ports, maintenance-dredging operations are required every 3.5 years [58]. As result the magnitude and direction of tidal currents will experiment significant and repetitive variations over long time horizons. The latter confirms the need of accounting for the effects of dredging operations, when planning the installation of tidal farms in depth-limited regions, like Ria de Ribadeo [31].

4. Dredging Associated Risk (DAR) indicator for depth-limited coastal areas

As mentioned in previous sections, tidal currents characteristic of shallow coastal regions are highly sensitive to natural and/or anthropogenic bathymetric changes. Among them, periodic dredging operations of marine navigation channels stand out. As a result, the magnitude and direction of tidal currents may be significantly altered, jeopardising the long term technical and economic viability of tidal farms located in depth-limited regions [31]. On these grounds, a novel risk indicator, Dredging Associated Risk (DAR), was developed *ad hoc*, with the aim of quantifying the uncertainty derived from dredging operations. DAR represents the fraction of time for a specific location, in which the relative difference between the magnitude of tidal currents for the pre- and post-dredging scenarios, is higher than an uncertainty threshold value (e.g. 10 %, 20 % and 30 %). Consequently, DAR ranges from zero (no risk) to one (maximum risk). DAR does not discriminate between increments and decrements of flow velocities, since both of them are considered equally harmful. For instance, a decrease of tidal flow velocities (after dredging), would result in significantly less power production and lower incomes for developers and investors. Conversely, significant increment of flow velocities (after dredging), could cause scour problems of bottom anchors and higher pressure loads on TEC structural elements, jeopardising the operating life of TECs. Lastly, when computing DAR, time-series of flow data (for the pre- and post-dredging scenarios) should cover a period of at least one year, with a minimum frequency of three hours, to account for the seasonal variations of the tidal-stream currents.

For the present study, pre- and post-dredging flow conditions were determined by means of the Delft3D-Flow hydrodynamic model [68]. For this purpose, two numerical models were set-up considering the bathymetric datasets corresponding with pre- and post-dredging scenarios, respectively. The simulations covered an average year, using as model inputs, time-series of mean monthly values of river discharges, wind magnitude and direction, salinity and temperature at the ocean boundaries. For further details, the readers are referred to Ref. [31], in which an exhaustive description of the model implementation and validation is presented. Consequently, DAR was computed based on annual hourly flow data, at each cell of the numerical hydrodynamic grid, which allows obtaining a spatial distribution of DAR for Ria de Ribadeo. Figure 6 presents the algorithm used to compute DAR. Finally, it is worth mentioning that DAR methodology can be applied elsewhere, considering also different values for the uncertainty thresholds.

5. Tidal farm siting for Ria de Ribadeo

5.1. Ria de Ribadeo: Resource characterisation

When considering the installation of tidal farms at Ria de Ribadeo, among the constraints presented in Section 3, the following stand out: (i) TEC operation must be respectful with the seabed, to preserve its archaeological heritage and (ii) TECs must meet the water depth limitations (approx. 4 *m* at LAT), present in the most energetic locations of the *ria*. Consequently, floating TECs appear as the most appropriate technology since, they are considerably less disruptive for the seabed than bottom-fixed TECs. In this context, the horizontal-axis, floating Evopod turbine, was used as reference for the identification of potential tidal farm sites. Table 3 summarises the main technical characteristics of the Evopod Turbine.

Based on the annual flow conditions of Ria de Ribadeo, computed by the hydrodynamic model presented in Section 4, the operativity of the Evopod turbine was analysed. For this purpose, the number of annual hours, for which flow velocity exceeds the *cut-in* of the turbine (Table 3), were determined. Figure 7 shows the results obtained. As can be observed, only the middle section of the *ria* presents adequate operational conditions for the Evopod turbine, with some areas easily exceeding 2200 operating hours per year. On these grounds, a detailed characterisation of the tidal stream resource was carried out for the middle section of the *ria*. For this purpose, the tidal resource was assessed on an annual basis, in contrast to the traditional approach, which is only based on the flow conditions of representative tidal cycles (e.g. spring-neap tidal cycle). Figure 8 shows the spatial distribution of annual energy density. As can be observed, areas A, B and C stand out in terms of tidal stream resource. Area A, with a total surface of 22 ha and annual energy densities in the order of 0.9 $GWhm^{-2}$, is the less energetic of the three, due to the blockage effect caused by the piles of the bridge that crosses the estuary. Area B, which covers a surface of 8.1 ha, presents also a larger tidal stream resource, with annual energy densities up to 1 $GWhm^{-2}$. Area C appears as the most suitable location from the energetic point of view, with an annual resource of 1.2 $GWhm^{-2}$, spanning a total surface of 10.9 ha. Finally, it is important to point out, that the results presented in Figures 7 and 8 are based on the pre-dredging flow conditions, which represents the most plausible scenario in the *ria*.

5.2. Ria de Ribadeo: Dredging Associated Risk (DAR)

With the purpose of quantifying the uncertainties derived from dredging operations, DAR was computed for Ria de Ribadeo following the algorithm presented in Figure 6 (Section 4). For this study, three different uncertainty levels (i.e. relative differences of flow velocities between pre- and post-dredging scenarios) of 10, 20 and 30 % were considered to illustrate the behaviour of DAR indicator. The results obtained confirm the necessity of including the effects of dredging in the decision-making process, when planning the installation of tidal farms in Ria de Ribadeo. As expected, DAR increases as the required level of uncertainty for the operating flow conditions decreases. For a level of uncertainty of 10%, DAR exceeds values of 0.8 (i.e. high risk) at the middle section of the *ria* (Figure 9.a), where the most energetic areas (A, B and C) are located (Section 5.1). Figure 9.b shows the DAR values for a level of uncertainty of 20%. In this case, DAR decreases considerably for the regions of interest (Areas A, B and C), with its maximum values up to 0.5 (i.e. mid risk). For an uncertainty threshold of 30%, DAR decreases dramatically across the *ria*, barely exceeding values of 0.2 (i.e. low risk) for Areas A, B and C (Figure 9.c). In consequence, the selection of uncertainty levels, which will depend mainly on the periodicity and extent of dredging operations and the risk aversion of developers and investors of tidal farm projects, play a significant role in DAR outputs. For instance, regions with frequent dredging operations during the useful life of the tidal farm (eg. every 4 or 5 years) should adopt a conservative uncertainty level of 10%. Conversely, for regions with a lower periodicity of dredging operations (7 to 10 years), higher uncertainty levels (20 or 30%) can be adopted. Regardless of the uncertainty level selected, it is recommended that regions with values exceeding 0.2 should be discarded for tidal farm operation since, for at least 20% of annual hours (1752 h) relative differences between pre- and post-dredging flow velocities exceed the uncertainty level selected (e.g. 10%). As result, tidal farms could present either lower power production (due to flow velocity reductions) or withstand harsher flow conditions (due to flow velocity increments), jeopardising their long-term economic or technical feasibility, respectively. In sum, DAR gives the opportunity to map tidal farm sites, identifying the regions with higher dredging-related risks, which may be very helpful for the decision-making of tidal farm projects, especially at depth-limited regions, which are normally subjected to periodic changes of bathymetric conditions.

5.3. Ria de Ribadeo: Tidal-stream sites

Following the exclusionary approach of the maritime legal framework applicable to Ria de Ribadeo (Sections 2 and 3.1), GIS mapping was used for the identification of potential tidal farm sites across the *ria*. For this purpose, geographical information of maritime exclusive areas (Section 3), tidal stream resource (Section 5.1), DAR spatial distribution (Section 5.2) and water depth limitations (Section 5.1), was combined. Figure 10 presents the results obtained. Maritime exclusive areas (60.6% of *ria* surface), highlighted in grey in Figure 10, are discarded for tidal farm operation, according to RD 1028/2007 (Section 2). In addition, water depth requirements of Evopod turbines (Table 2), limit their operation to water depths of at least 4 m. Consequently, only East sectors of Areas A and C can be considered appropriate for tidal farm operation (marked as Level II areas in Figure 10). Among them, Area A appears as the most suitable location for locating a tidal farm, with an annual energy density exceeding 1 $GWhm^{-2}$ and a total surface of approximately 5.6 ha.

Furthermore, Figure 11 presents the DAR distribution values for the tidal farm sites previously identified (Areas A and C). Overall, as the requirements in terms of level of uncertainty (i.e. relative differences of flow velocities between pre- and post-dredging scenarios) are softened, the usable surface of tidal sites increases. For a level of uncertainty of 10% (Figure 11.a), most part of Area C presents DAR values exceeding 0.8 (i.e. after dredging magnitude of tidal currents vary more than 10% at least for 80% of annual hours) and, therefore, should be discarded for tidal farm operation. Conversely, Northern sectors of Area A (Figure 11.a), which span a total surface area of 42.3 ha and with annual energy densities of 0.5 $GWhm^{-2}$, are suitable for tidal stream exploitation since, DAR presents values lower than 0.2. Raising the level of uncertainty up to 20% (Figure 11.b), translates into a surface increment of 0.58 ha in Area A, mainly concentrated in its southern sector. Finally, assuming higher levels of uncertainty (e.g. 30%), the majority of

Areas A and C become available for the installation of tidal farms (Figure 11.c). According to the high periodicity of dredging operations (every 3.5 years) and their significant impacts on the flow conditions of Areas A and C, the results obtained for the most restrictive DAR uncertainty level (10%) should be retained for the implementation of tidal farms. Finally, Table 4 summarises the usable surface of Areas A and C for the different DAR uncertainty levels considered.

6. Conclusions

In 2014 the European Commission released Directive 2014/89/EU on Maritime Spatial Planning, whose main goals are to ensure a harmonic coexistence among different maritime activities and to protect the marine environment. Regarding MRE exploitation, Directive 2014/89/EU offers the opportunity to improve and harmonise the legal framework for licensing MRE projects, increase legal security for MRE stakeholders and reduce/arbitrate conflicts with other maritime users. For the specific case of Spain, Directive 2014/89/EU was transposed by means of RD 363/2017, which identifies MRE as a relevant activity to be considered for the elaboration of future Maritime Spatial Plans (MSPs). According to previous marine legislation (RD 1028/2007), MSPs are expected to present a zoning approach, consisting of maritime exclusive areas. In this context, the objective of the present work is to present a methodology using Marine Spatial Planning (MSP) tools, to locate tidal stream energy farms at depth-limited regions. For this purpose, Ria de Ribadeo (NW Spain) a shallow coastal embayment, with a substantial tidal stream energy resource, was used as case study.

In general terms, the application of MSP tools for tidal farm siting appears to perform well for the present case study, identifying appropriate locations for tidal farm operation, avoiding potential conflicts with other maritime activities (fishing, aquaculture, navigation and recreational) and preserving biological and archaeological heritages of Ria de Ribadeo. After the identification of maritime exclusive areas only two exploitable tidal farm sites (Areas A and C), with values of annual energy density up to 1 $GWhm^{-2}$, were found. However, potential disruptions on tidal farm operating conditions, derived from other maritime activities, must be also included as part of MSP. In the case of Ria de Ribadeo, periodic dredging of navigation channels may impact significantly the tidal currents of Areas A and C, which translates into high levels of uncertainty in terms of power production. In this context, a site-specific risk indicator, Dredging Associated Risk (DAR), was developed *ad hoc*. DAR ranges from zero (no risk) to one (maximum risk), representing the fraction of annual hours, in which relative differences between pre- and post-dredging flow velocities, exceed an uncertainty threshold percentage. For the tidal farm sites identified, DAR exceeds values of 0.8 (high risk), highlighting the importance of accounting for the disruptions caused by other maritime activities, in this case dredging operations, when planning the installation of tidal farms using MSP tools. Based on the results obtained, the authors recommended that areas with DAR values exceeding 0.2 (i.e. after dredging tidal flow velocities vary more than the uncertainty threshold defined by DAR users, for at least 20% of annual hours) should be discarded for tidal farm operation. According to this criterium, the exploitable surface for tidal sites A and C, decreases 25% and 98%, respectively. It is important to note, that DAR can be applied elsewhere, using different values of threshold uncertainty levels. Finally, the recommended DAR limit to discard tidal farms sites must be considered as a first indication and should be corroborated by further research at different locations.

In summary, this paper presents a MSP-based methodology for tidal farm siting, accounting for the risks associated to anthropogenic bathymetric changes, which are especially relevant for depth-limited regions. Nonetheless, additional constraints relevant for tidal farm siting, such as distances to grid connection points, seabed geology and socio-economic aspects are not considered in this work and will be dealt with as a continuation of this research.

Acknowledgments

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Figure Captions

Figure 1: Location of Ria de Ribadeo.

Figure 2: Linkages between Spanish maritime legislation.

Figure 3: Special Areas of Conservation (SACs), Special Protection Areas for Birds (SPABs) and North-Atlantic Marine Demarcation (NAMD) areas at Ria de Ribadeo.

Figure 4: Archaeological protected areas at Ria de Ribadeo.

Figure 5: GIS mapping of exclusive maritime zones at Ria de Ribadeo.

Figure 6: Algorithm for the calculation of Dredging Associated Risk (DAR) indicator

Figure 7: Spatial distribution of annual operating hours for the Evopod Turbine

Figure 8: Spatial distribution of annual energy density for Ria de Ribadeo

Figure 9: DAR spatial distribution for Ria de Ribadeo. (a) Uncertainty Level of 10%. (b) Uncertainty Level of 20%. (c) Uncertainty Level of 30%.

Figure 10: GIS mapping for tidal farm siting at Ria de Ribadeo

Figure 11: DAR levels for potential tidal sites at Ria de Ribadeo

Figure1

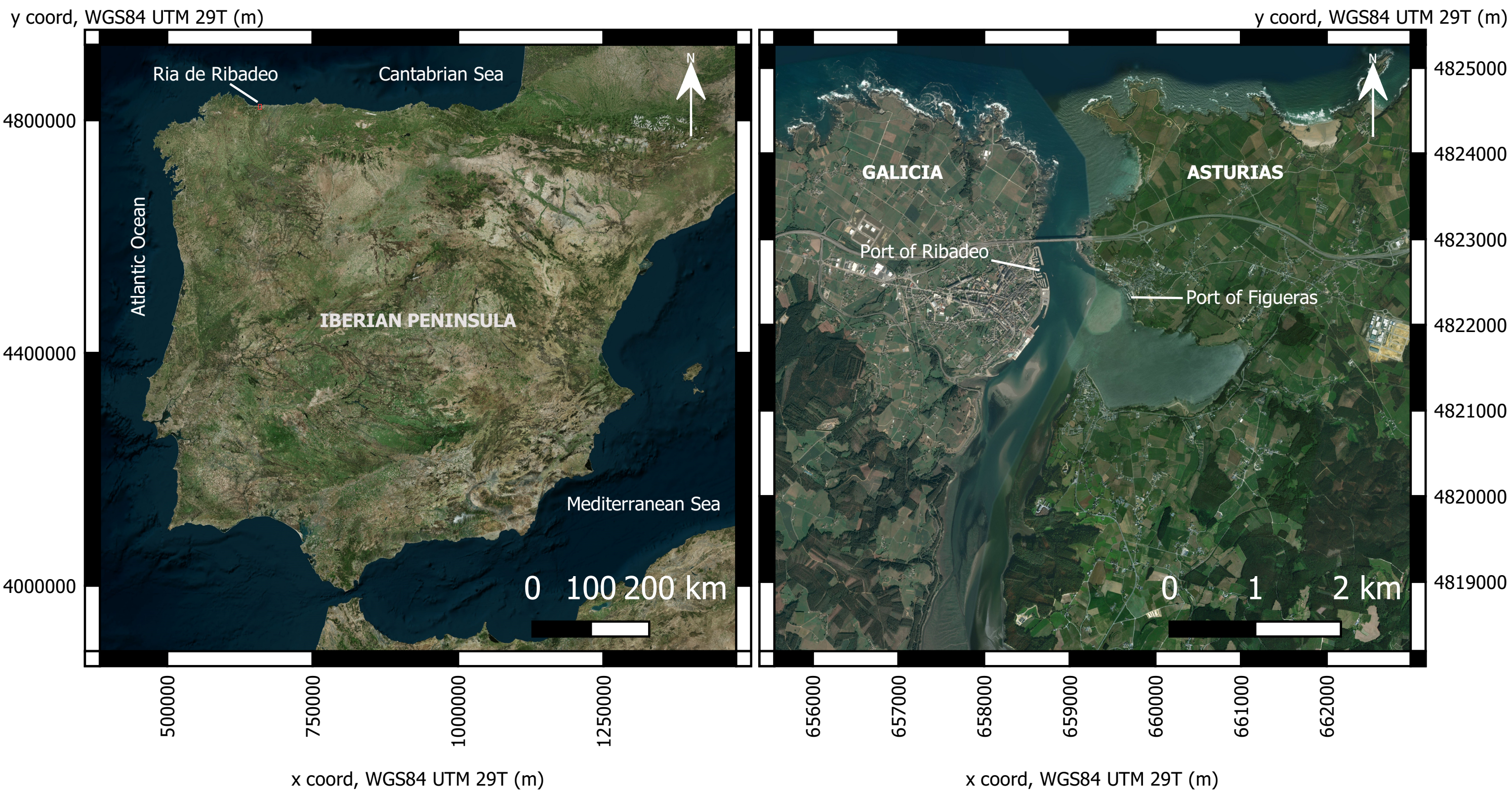
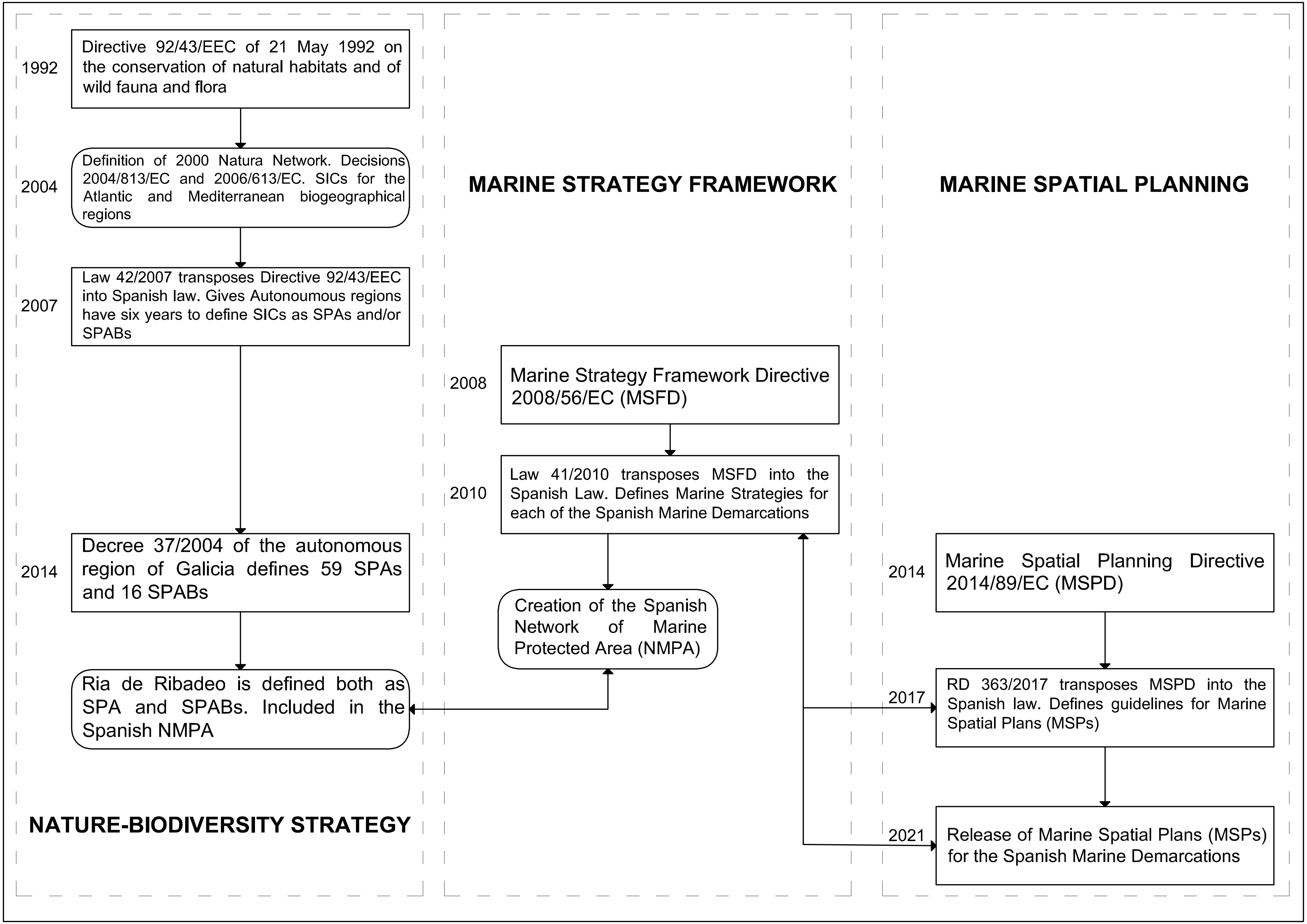
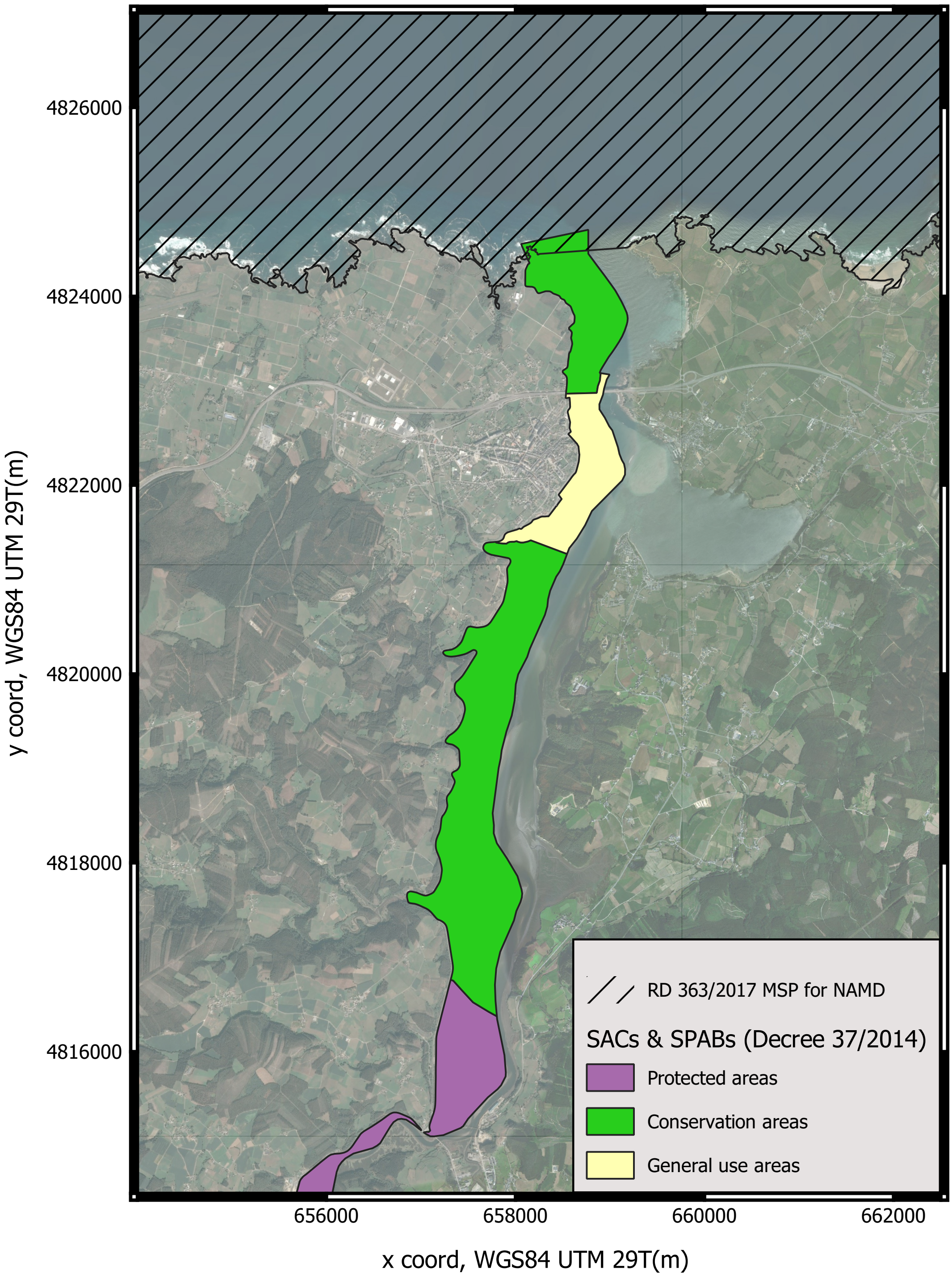

y coord, WGS84 UTM 29T (m)
Ria de Ribadeo
Cantabrian Sea
Atlantic Ocean
IBERIAN PENINSULA
Mediterranean Sea
N
0 100 200 km
4800000
4400000
4000000
500000
750000
1000000
1250000
x coord, WGS84 UTM 29T (m)
y coord, WGS84 UTM 29T (m)
GALICIA
ASTURIAS
Port of Ribadeo
Port of Figueras
N
0 1 2 km
4825000
4824000
4823000
4822000
4821000
4820000
4819000
656000
657000
658000
659000
660000
661000
662000
x coord, WGS84 UTM 29T (m)

Figure2



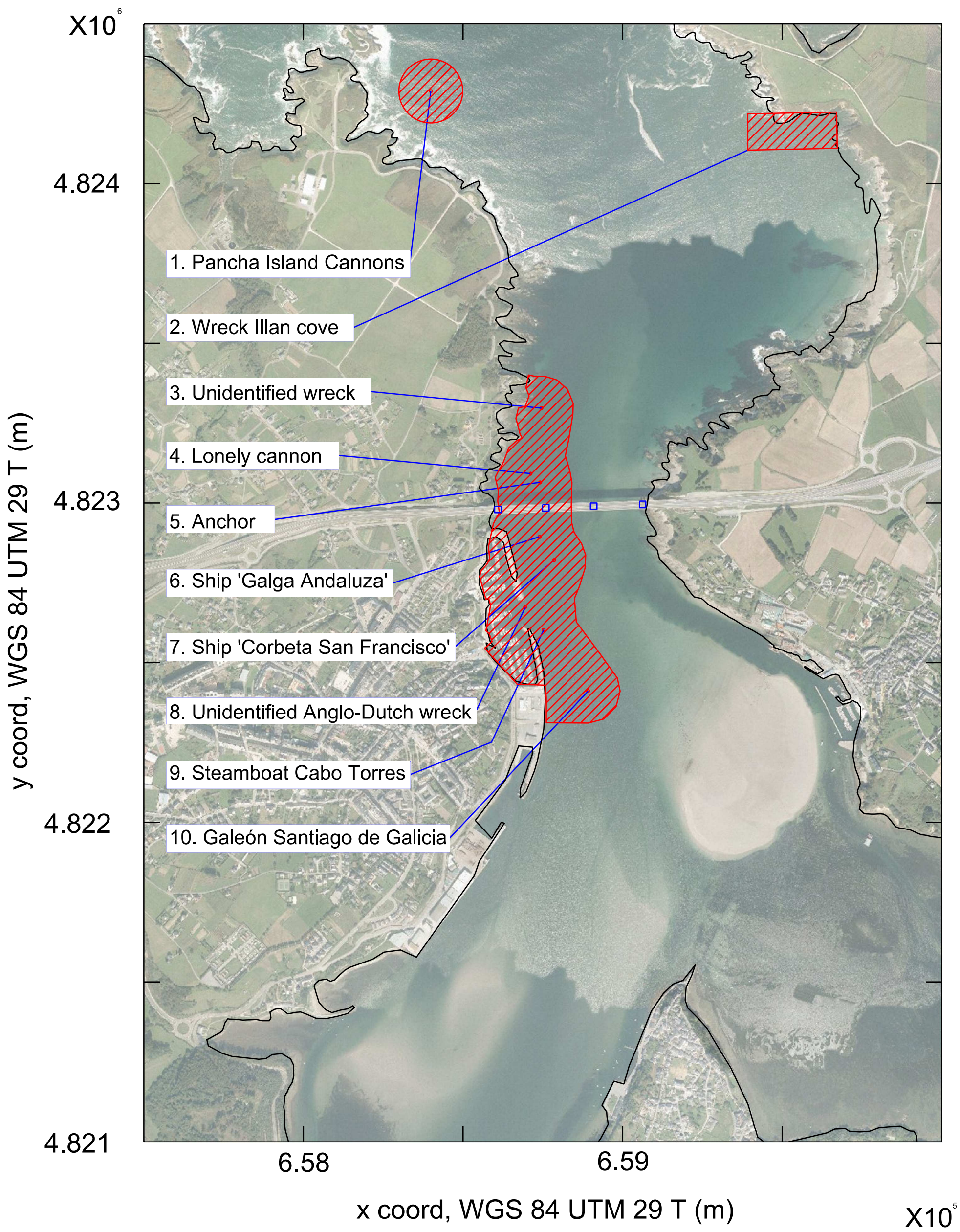
1992
Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora
2004
Definition of 2000 Natura Network. Decisions 2004/813/EC and 2006/613/EC. SICs for the Atlantic and Mediterranean biogeographical regions
2007
Law 42/2007 transposes Directive 92/43/EEC into Spanish law. Gives Autonoumous regions have six years to define SICs as SPAs and/or SPABs
2014
Decree 37/2004 of the autonomous region of Galicia defines 59 SPAs and 16 SPABs
Ria de Ribadeo is defined both as SPA and SPABs. Included in the Spanish NMPA
NATURE-BIODIVERSITY STRATEGY
MARINE STRATEGY FRAMEWORK
2008
Marine Strategy Framework Directive 2008/56/EC (MSFD)
2010
Law 41/2010 transposes MSFD into the Spanish Law. Defines Marine Strategies for each of the Spanish Marine Demarcations
Creation of the Spanish Network of Marine Protected Area (NMPA)
MARINE SPATIAL PLANNING
2014
Marine Spatial Planning Directive 2014/89/EC (MSPD)
2017
RD 363/2017 transposes MSPD into the Spanish law. Defines guidelines for Marine Spatial Plans (MSPs)
2021
Release of Marine Spatial Plans (MSPs) for the Spanish Marine Demarcations

Figure3



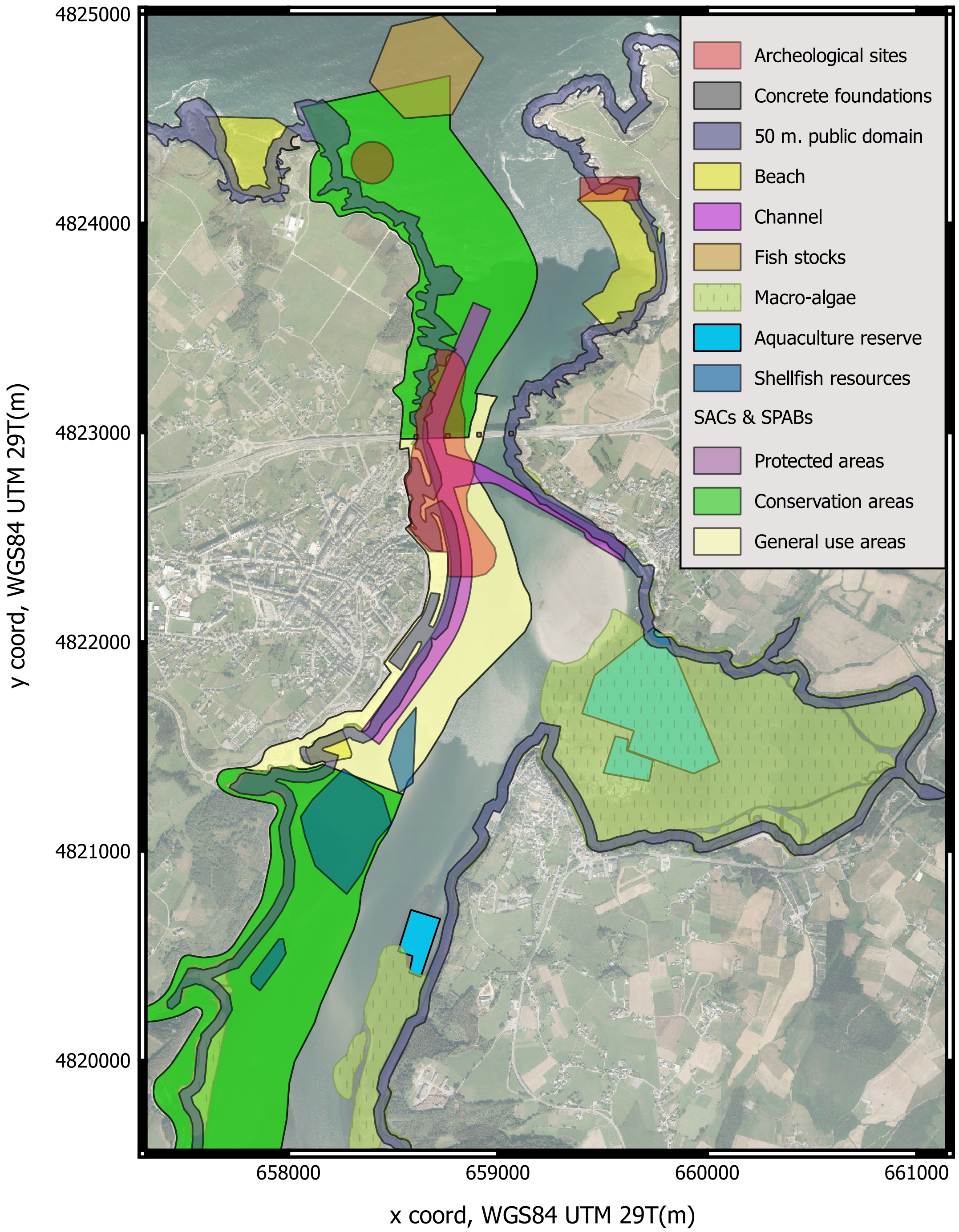
4826000
4824000
4822000
4820000
4818000
4816000
y coord, WGS84 UTM 29T(m)
656000
658000
660000
662000
x coord, WGS84 UTM 29T(m)
RD 363/2017 MSP for NAMD
SACs & SPABs (Decree 37/2014)
Protected areas
Conservation areas
General use areas

Figure4



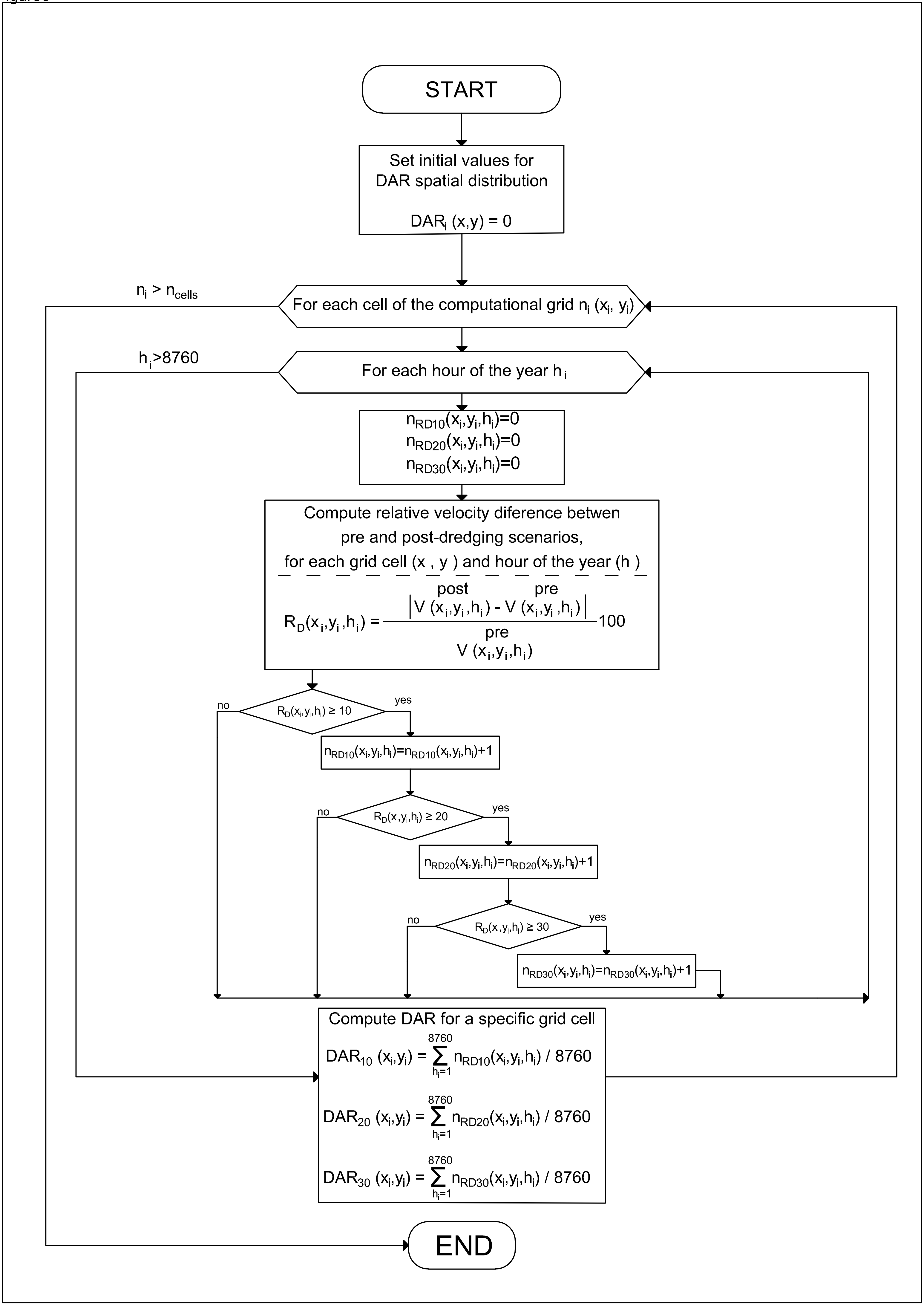
X10^6
4.824
4.823
4.822
4.821
y coord, WGS 84 UTM 29 T (m)
6.58
6.59
x coord, WGS 84 UTM 29 T (m)
X10^5
1. Pancha Island Cannons
2. Wreck Illan cove
3. Unidentified wreck
4. Lonely cannon
5. Anchor
6. Ship 'Galga Andaluza'
7. Ship 'Corbeta San Francisco'
8. Unidentified Anglo-Dutch wreck
9. Steamboat Cabo Torres
10. Galeón Santiago de Galicia

Figure5



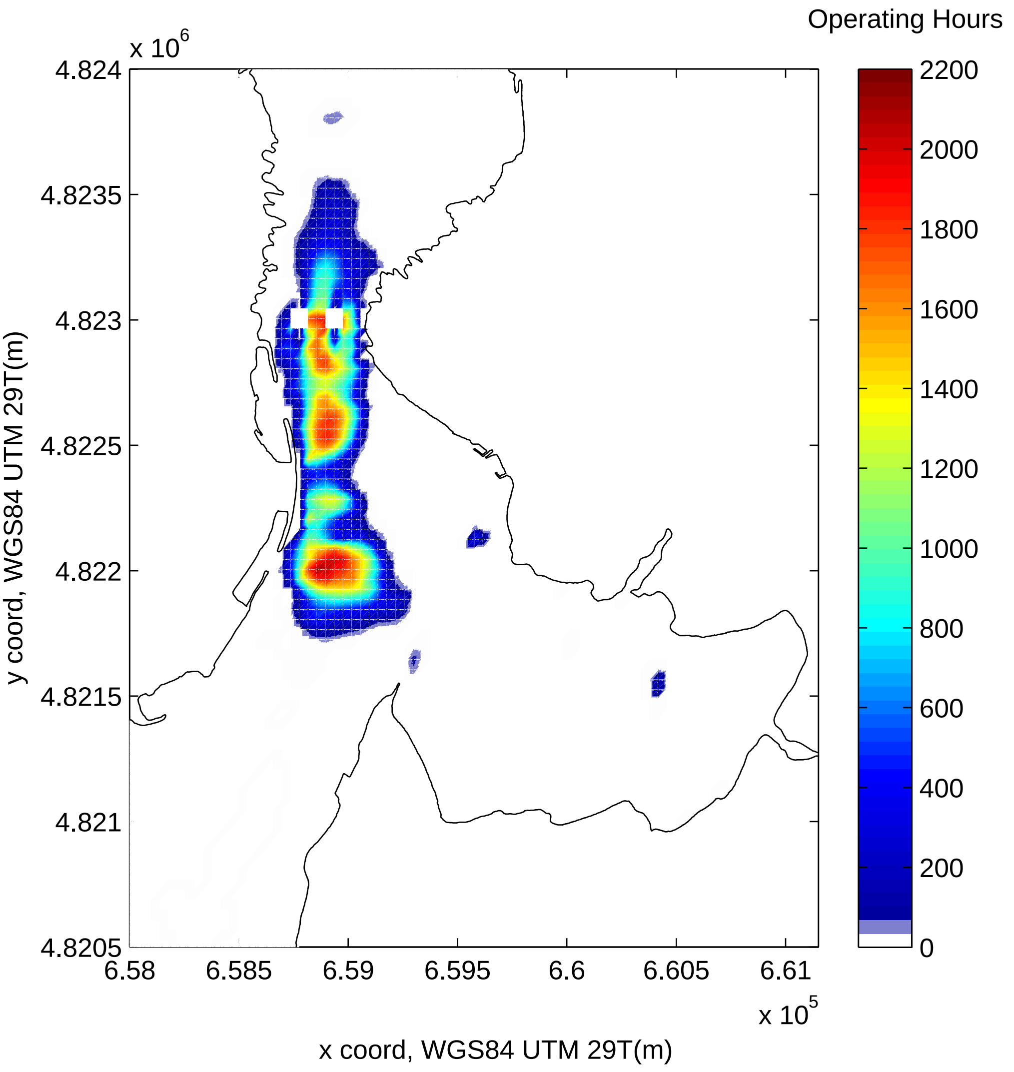
Archeological sites
Concrete foundations
50 m. public domain
Beach
Channel
Fish stocks
Macro-algae
Aquaculture reserve
Shellfish resources
SACs & SPABs
Protected areas
Conservation areas
General use areas
4825000
4824000
4823000
4822000
4821000
4820000
658000
659000
660000
661000
y coord, WGS84 UTM 29T(m)
x coord, WGS84 UTM 29T(m)

Figure6



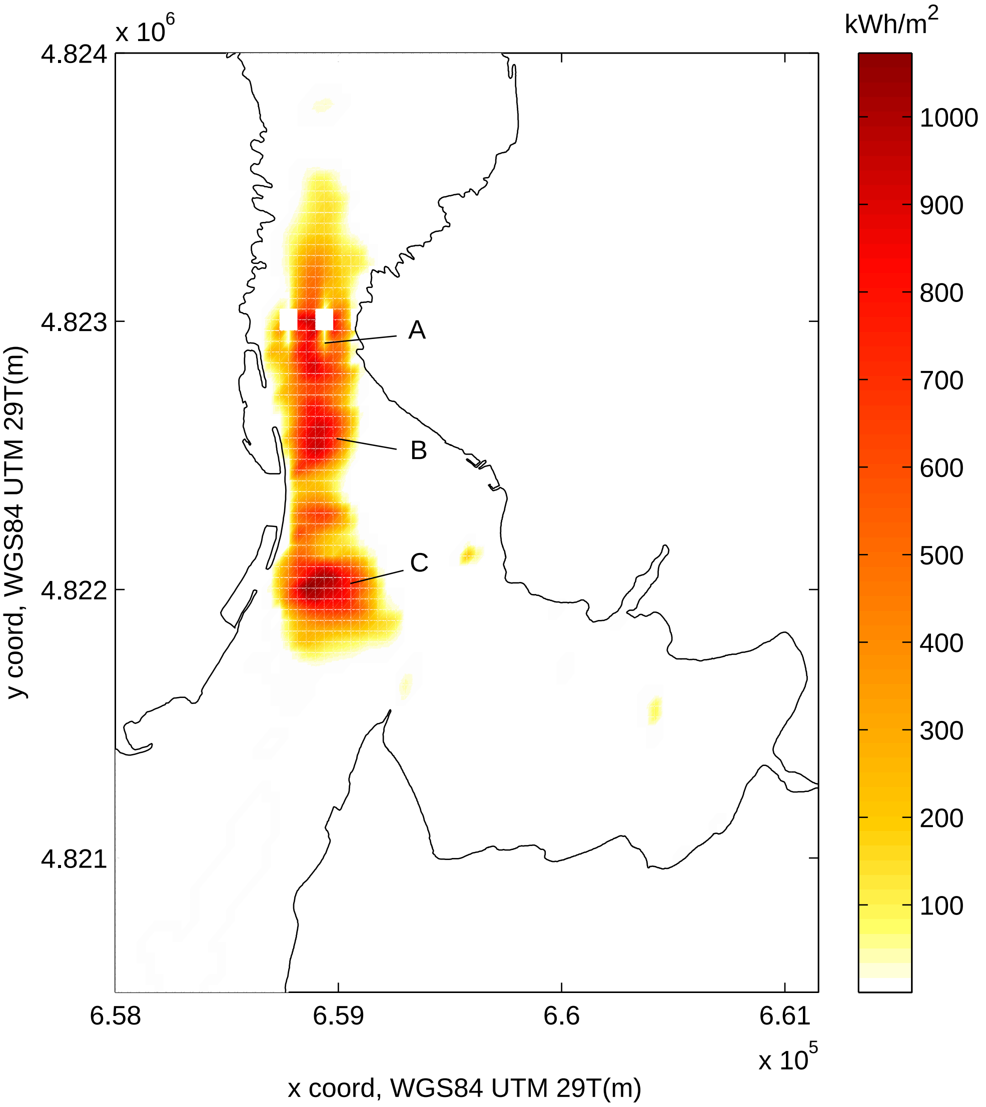
START
Set initial values for DAR spatial distribution
DAR_i (x,y) = 0
n_i > n_cells
For each cell of the computational grid n_i (x_i, y_i)
h_i>8760
For each hour of the year h_i
n_RD10(x_i,y_i,h_i)=0
n_RD20(x_i,y_i,h_i)=0
n_RD30(x_i,y_i,h_i)=0
Compute relative velocity diference betwen pre and post-dredging scenarios, for each grid cell (x , y) and hour of the year (h)
R_D(x_i,y_i,h_i) = |V^post(x_i,y_i,h_i) - V^pre(x_i,y_i,h_i)| / V^pre(x_i,y_i,h_i) 100
no
R_D(x_i,y_i,h_i) ≥ 10
yes
n_RD10(x_i,y_i,h_i)=n_RD10(x_i,y_i,h_i)+1
no
R_D(x_i,y_i,h_i) ≥ 20
yes
n_RD20(x_i,y_i,h_i)=n_RD20(x_i,y_i,h_i)+1
no
R_D(x_i,y_i,h_i) ≥ 30
yes
n_RD30(x_i,y_i,h_i)=n_RD30(x_i,y_i,h_i)+1
Compute DAR for a specific grid cell
DAR_10 (x_i,y_i) = Σ_{h_i=1}^{8760} n_RD10(x_i,y_i,h_i) / 8760
DAR_20 (x_i,y_i) = Σ_{h_i=1}^{8760} n_RD20(x_i,y_i,h_i) / 8760
DAR_30 (x_i,y_i) = Σ_{h_i=1}^{8760} n_RD30(x_i,y_i,h_i) / 8760
END

Figure7



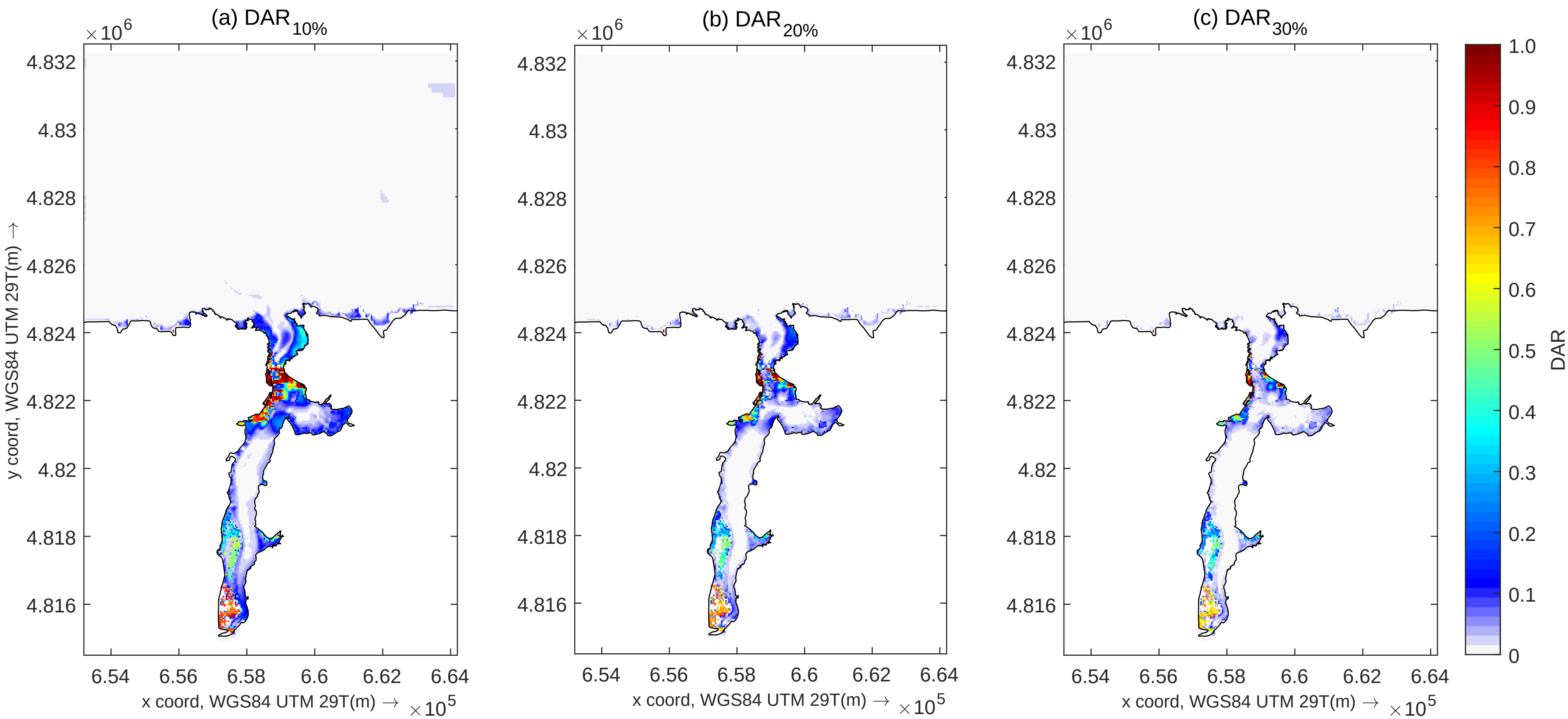
Operating Hours
x 10^6
4.824
4.8235
4.823
4.8225
4.822
4.8215
4.821
4.8205
y coord, WGS84 UTM 29T(m)
6.58
6.585
6.59
6.595
6.6
6.605
6.61
x 10^5
x coord, WGS84 UTM 29T(m)
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0

Figure8



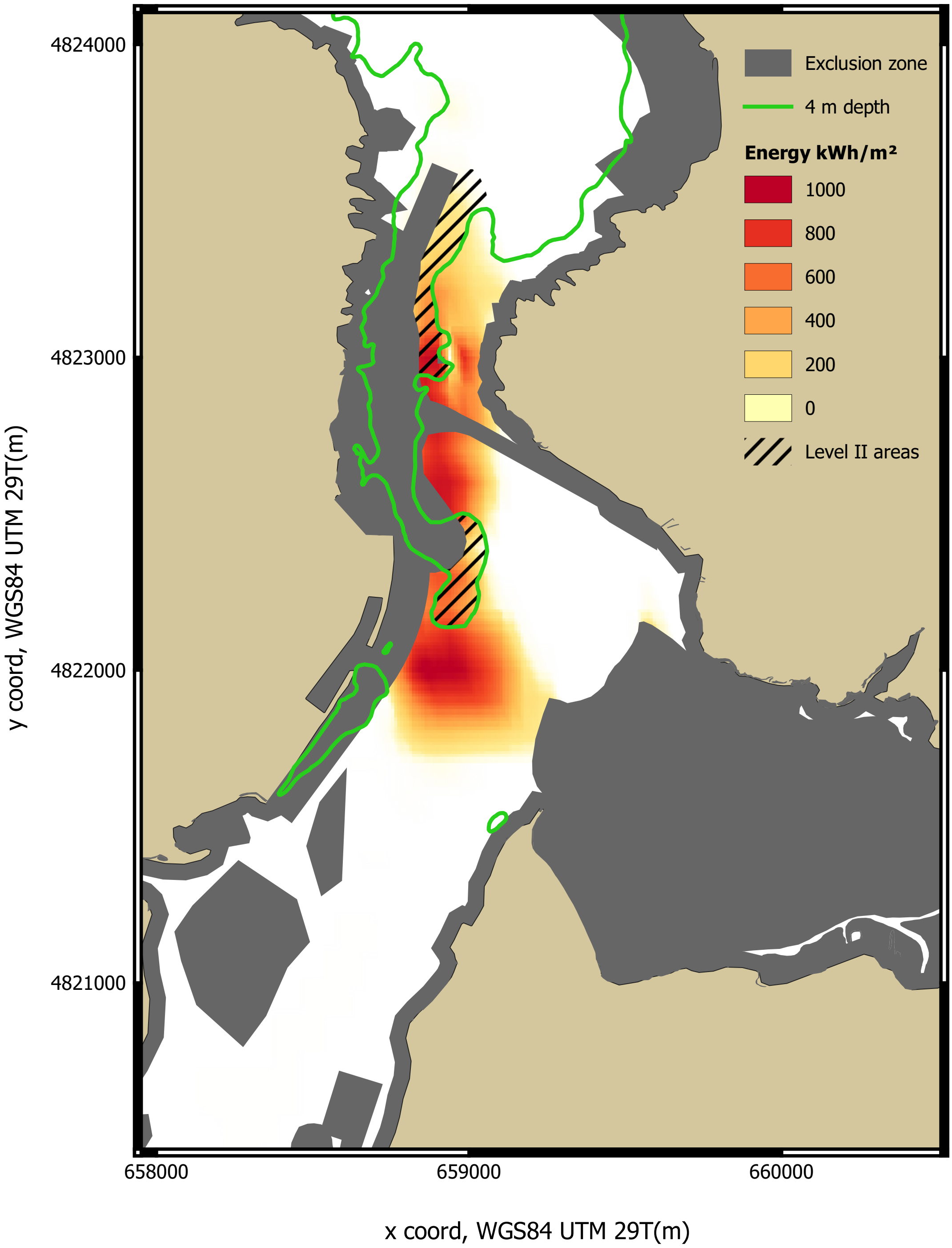
x 10^6
4.824
4.823
4.822
4.821
y coord, WGS84 UTM 29T(m)
A
B
C
6.58
6.59
6.6
6.61
x 10^5
x coord, WGS84 UTM 29T(m)
kWh/m^2
1000
900
800
700
600
500
400
300
200
100

Figure9



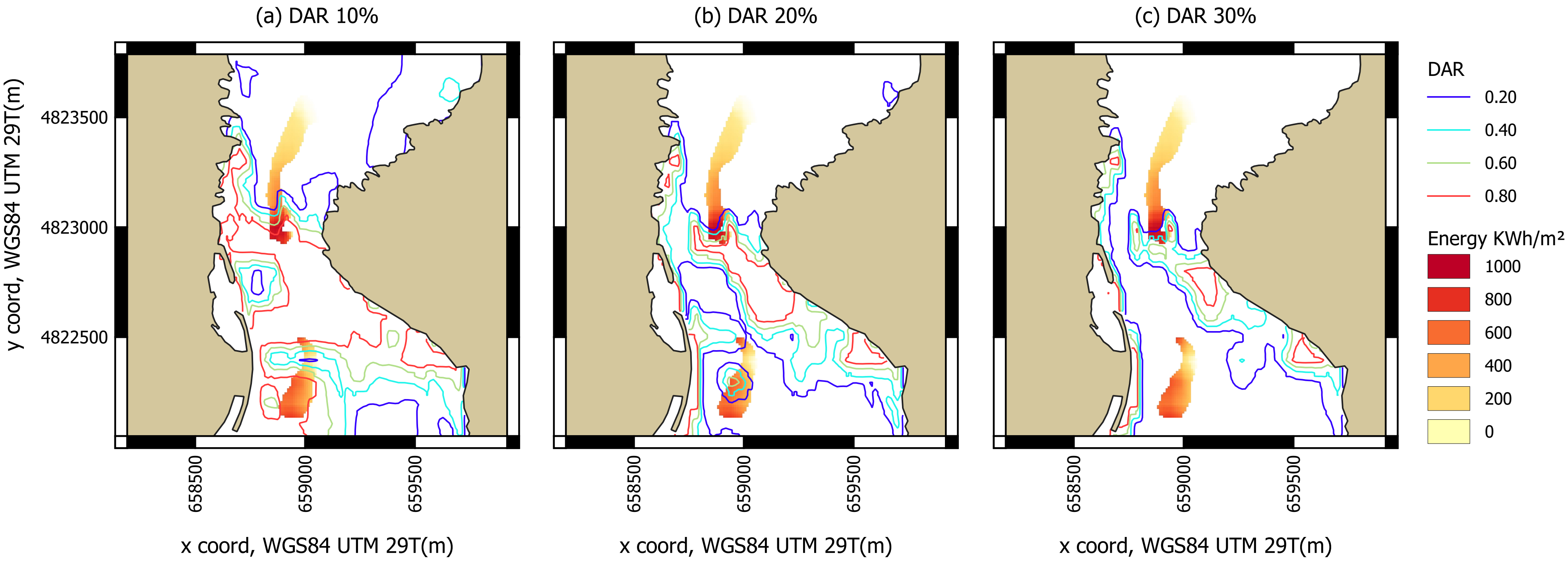
(a) DAR10%
(b) DAR20%
(c) DAR30%
×10^6
4.832
4.83
4.828
4.826
4.824
4.822
4.82
4.818
4.816
y coord, WGS84 UTM 29T(m) →
6.54
6.56
6.58
6.6
6.62
6.64
x coord, WGS84 UTM 29T(m) →
×10^5
DAR
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

Figure10



Exclusion zone
4 m depth
Energy kWh/m²
1000
800
600
400
200
0
Level II areas
4824000
4823000
4822000
4821000
658000
659000
660000
y coord, WGS84 UTM 29T(m)
x coord, WGS84 UTM 29T(m)

Figure11



(a) DAR 10%
(b) DAR 20%
(c) DAR 30%
y coord, WGS84 UTM 29T(m)
4823500
4823000
4822500
658500
659000
659500
x coord, WGS84 UTM 29T(m)
DAR
0.20
0.40
0.60
0.80
Energy KWh/m²
1000
800
600
400
200
0

Table1

	Description
Pancha Island Cannon	3 pieces of iron artillery
Wreck Illán cove	12 iron cannons with ammunition Valuable ceramic remains Remains of the hull of an unknown wreck.
Unidentified wreck	Unknown wreck of the 18^{th} century
Lonely cannon	Cannon belonging to an unknown wreck
Anchor	Anchor belonging to an undiscovered wreck
Ship Galga Andaluza	Spanish pirate ship
Ship Corbeta San Francisco	Spanish pirate ship
Steamship Cabo Torres	Merchant ship sunk in 1887
Galeón Santiago de Galicia	Ship of the Spanish Navy (XVI century). Considered the best preserved Spanish galleon

Table 1: Main characteristics of the archaeological remains found in Ria de Ribadeo

Table2

	Surface (ha)
Archaeological sites	32.64
Fishing and shell-fishing grounds	38.64
Aquaculture sites	30.77
Macro-Algae sites	289.55
Public domain areas	155.04
Beach areas	31.29
Navigation channels	28.43

Table 2: Surface of Maritime exclusive areas

Table3

Type	Floating
Diameter (m)	3
Cut-in velocity (ms^{-1})	0.7
Cut-off velocity (ms^{-1})	3.0
Rated velocity (ms^{-1})	1.9
Rated power (kW)	25

Table 3: Main technical characteristics of the Evopod Turbine

Table4

	Area A	**Area B**	**Area C**
Total Surface (*ha*)	22.2	8.2	10.9
Usable Surface (*ha*)	5.6	–	3.4
$DAR_{10\%}$ usable surface (*ha*)	4.3	–	0.06
$DAR_{20\%}$ usable surface (*ha*)	4.8	–	1.9
$DAR_{30\%}$ usable surface (*ha*)	4.9	–	3.4

Table 4: Surface of tidal sites A, B and C